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ERRATA FOR:

ADVANCED SOLAR THERMIONIC GENERATORS

QUARTERLY TECHNICAL PROGRESS REPORT NO. 3
JUNE 1963
AF 33(657)-8947

Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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GENERAL ELECTRIC
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Page ii Should be:

The work covered by this report was accomplished under Air Force Contract AF 33(657)-8947, but this report is being published and distributed prior to Air Force review. The publication of this report, therefore, does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

Page iii, line 5 should be:

AF Aero Propulsion Laboratory, Aeronautical Systems Division

Page vii Abstract should be:

Efforts were concentrated on development of new converters for the generator. A pin-tensile rod technique for positive electrode spacing was developed and incorporated in the converter design. Various combinations of emitter-collector materials are being utilized for evaluation and selection in the final design. A suitable method of welding a rhenium emitter to the supporting tantalum structure was evolved and utilized in one converter. Data on the 4 converters processed and tested thus far are tabulated below. An additional 8 converters, mainly with rhenium emitters, are in the final stages of assembly.

Converter	Electrode Materials	Remarks
B-1	Ta-Ni	6 w/cm^2 at 1950^{o}K initially. 4 w/cm^2 during last 60 hours. Still operable after 90 hrs
B-2	Mo-Ni	6.3 w/cm^2 at 1950^{o}K initially. 9.6 w/cm^2 during last 25 hours. Still operable after 95 hours.
B-4	Re-Ni	5 w/cm^2 at 1950^{o}K initially. Test continuing
C-3	Ta-Ta	2.8 w/cm^2 at 1950^{o}K initially. 2 w/cm^2 at 500 hours. Still operable after 522 hours (including 210 hours thermal cycling).

ADVANCED SOLAR THERMIONIC GENERATORS

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FOREWORD

This report covers work completed during March, April and May of 1963; by the General Electric Company, Missile and Space Division, Spacecraft Department at Philadelphia, Pa. on Air Force Contract No. AF 33(657)-8947, Project No. 8173, Task No. 817305-16, "Advanced Solar Thermionic Generators." The work was administered under the guidance of A. E. Wallis, Flight Accessories Laboratory, Aeronautical Systems Division.

General Electric personnel who actively participated in this work are:

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ABSTRACT

Fabrication of development converters, both B and C series, is outlined, noting the significant problem areas. Results of testing of the B series have given performance up to 9.6 watts/cm^2 at 1950°K and 3.0 watts/cm^2 at 1550°K. Converter C-3 has completed a 510 hour life test, including 210 hours of thermal cycling.

INTRODUCTION

The effort on STEPS III during this quarter has been concentrated on demonstrating adequate performance and life for the new converters. To achieve this, a life test of 510 hours has been specified for the C Series converters, which includes both steady state and thermal cycling operation. The thermal cycling portion consists of 140 cycles of 60 minutes on and 30 minutes off, simulating low earth orbital conditions. The objective of the test is to pinpoint any design weaknesses that may cause excessive power degradation or outright failure. Information obtained from the life and performance testing will be used to improve the design and fabrication procedures, directly leading to another series of converters to be used in generator testing. Fabrication of the STEPS III generator has been postponed until performance and life have been demonstrated on the current series of converters.

1.0 CONVERTER FABRICATION

1.1 Summary of Converter Fabrication

Fabrication of converter B-4 and the first two converters of the C Series, C-3 and C-4, were completed during this quarter. Three B Series converters have now been fabricated, and Reference 2 showed a picture of one of these converters as test. The B Series converters are the following:

Converter	Cathode Material	Anode Material	Spacing Inches	Fabrication Status
B-1	Ta	Ni	.005	Complete
B-2	Mo	Ni	.005	Complete
B-3	Re	Ni	.005	Final Assembly
B-4	Re	Ni	.0025	Complete

The C Series converters, of which two have completed fabrication, are:

Converter	Cathode Material	Anode Material	Spacing Inches	Fabrication Status
C-1	Re	Mo	.002	Final Assembly
C-2	Re	Mo	.002	Final Assembly
C-3	Ta	Ta(Oxy)*	.005	Complete
C-4	Ta	Ta(Oxy)*	.002	Complete
C-5	Re	Ta(Oxy)*	.002	Final Assembly
C-6	Re	Ta(Oxy)*	.002	Final Assembly
C-7	Re	Re	.002	Final Assembly
C-8	Re	Re	.002	Final Assembly

Converter C-3 is shown in Figures 1 and 2. Parts of the converter prior to assembly are shown in Figure 3. All of the C Series converters will have the same external appearance, and the same mechanical characteristics with the exception of the cathode-anode materials and the spacing. The converter fin has been designed to form the external frame of a cubical generator. A complete description of the converter and accompanying generator design is given in Reference 2.

The fabrication of the converters has proceeded with only one major assembly problem, that of the weld between the rhenium cathode and tantalum sleeve. This problem has been solved so that in both the B&C Series, all converter subassemblies which started into final assembly have been successfully fabricated into operating converters.

All B and C Series converters have the cathode-anode spacing held constant, both hot and cold, by six tungsten pins between the anode and cathode. An alumina insulator recessed into the anode provides both electrical and thermal insulation. Pressure on the pins is maintained by a spring loaded tungsten tensile rod welded into the cathode and extending through the anode. A flexible bellows in the envelope below the seal allows for thermal expansion mismatches.

1.2 Rhenium Cathode Welds

Initial attempts to electron-beam weld the rhenium cathodes to the tantalum envelopes on converters B-3 and B-4 met with failure to achieve a leak tight weld. Subsequent tests on rhenium-tantalum test welds showed that an extremely brittle phase was

*Oxygenated

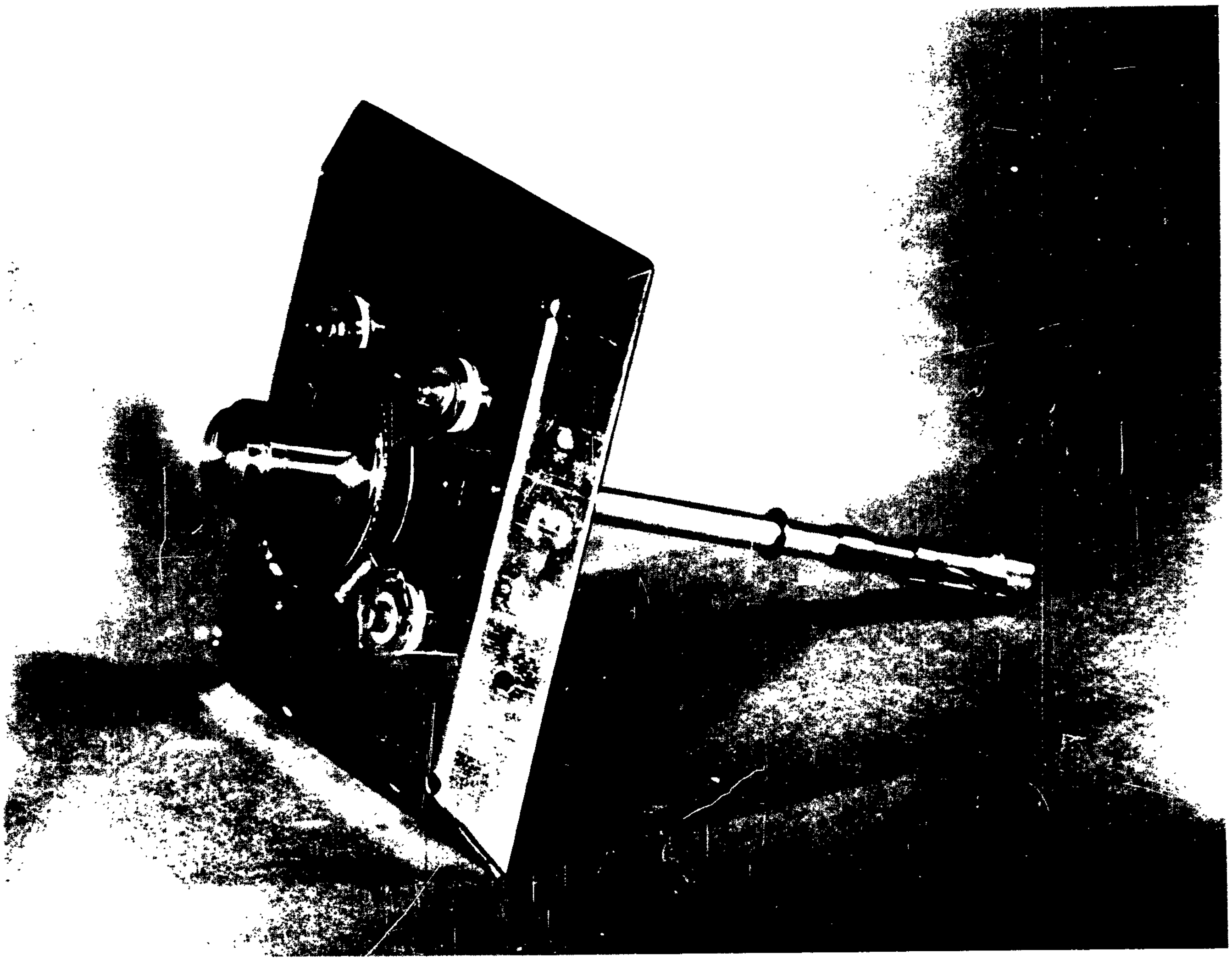


Figure 1. STEPS III Converter C-3 - Complete Assembly

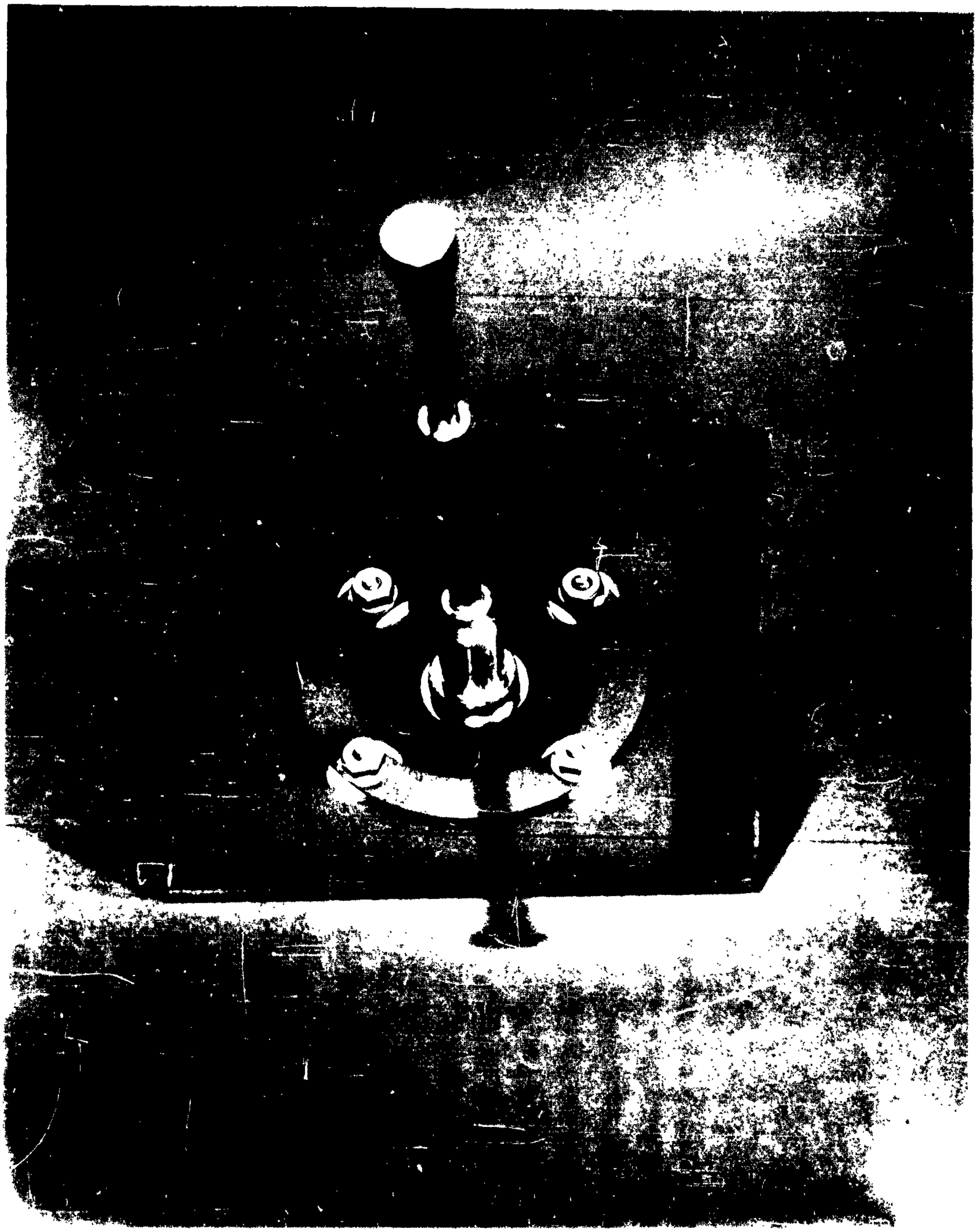


Figure 2. STEPS III Converter C-3 - Anode Fin and Cesium Tube

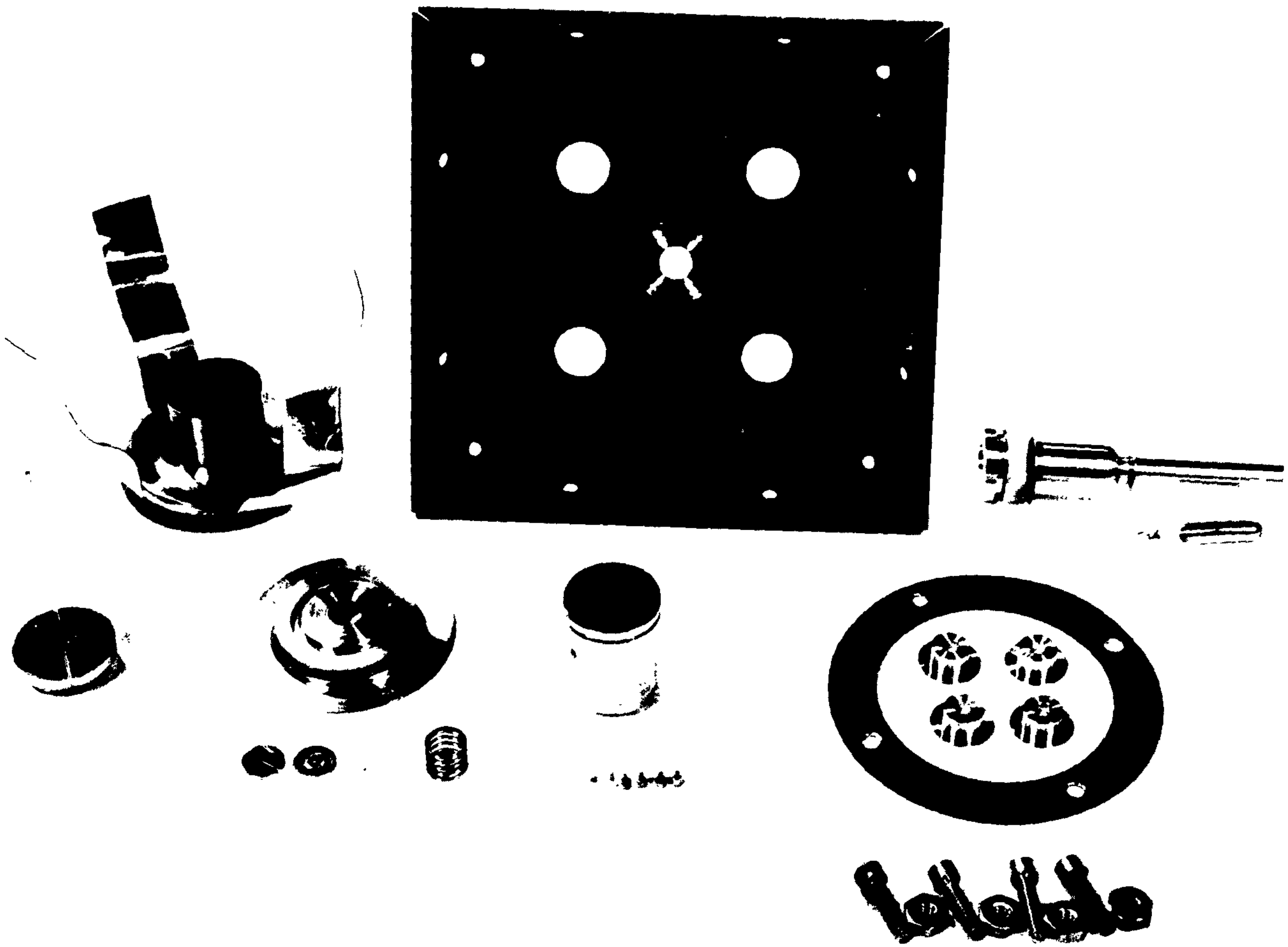


Figure 3. Parts for Converter C-3 Prior to Final Assembly

being produced in the weld. An earlier attempt to weld rhenium to tantalum on a test specimen of the same configuration had produced a successful leak tight weld. This specimen had remained leak tight after thermal cycling to 2000°K through eight cycles. The reason for this success was apparently very shallow penetration with the electron-beam which produced a thin weld region capable of relieving itself under thermal cycling. In order to produce a leak tight weld the following program of weld investigation was initiated:

1. Various preheating and slow melting of the weld region with the electron-beam welder was attempted. Although these attempts produced a reduction in the severity of the cracking, a basically brittle interface remained.

2. A molybdenum or iridium filler wire was introduced in the weld region in order to produce a more ductile alloy. This approach was abandoned due to the fact that it was difficult to achieve good thermal contact between the wire and the weld region. This led to uneven melting of the filler wire and a poor weld. Cracking was drastically reduced, however, particularly with the molybdenum filler.

3. Molybdenum powder was also introduced in the weld region in order to attempt to alleviate the thermal contact problem and uneven melting. The powder tended to spatter under the high-energy beam and no valid results were obtained.

4. A molybdenum ring was fitted around the periphery of the cathode slug on the side away from the emitting surface. The rhenium-molybdenum weld was made first, and then the tantalum-molybdenum weld. This approach was based on the rhenium-molybdenum system being more ductile than the rhenium-tantalum system. Also welds between molybdenum and the tantalum sleeve have been readily accomplished. The first test specimen using this configuration was successfully leak tight in both welds. The piece was thermally cycled to 2000°K and remained leak tight.

   The molybdenum ring has been incorporated in the fabrication of Converter B-4. The weld on B-4 was accomplished with no difficulty, was cycled to 2000°K, and has performed satisfactorily through initial converter testing. The C Series converters have now been modified to incorporate this weld configuration.

1.3 Fin Braze Tests

The joints between the molybdenum anode pedestal, the niobium seal members, the copper radiating fin, and the nickel cesium reservoir bushing are all brazed joints. These joints form part of the vacuum envelope of the converter with the exception of the braze between the molybdenum anode pedestal and the niobium seal section. Due to the difference in thermal expansion of these materials, shown in Figure 4, the life of these brazes under thermal cycling was investigated prior to assembly of any C Series converters.

A test specimen of this braze assembly was fabricated and leak checked to insure initial tightness. The assembly was then mounted in a vacuum system and the molybdenum anode was heated by electron bombardment. The bombardment power was adjusted to produce a fin temperature of 600°C at the root of the radiating fin. This is approximately the temperature at which the fin is to operate with a cathode temperature of 1680°C. The cycle was adjusted so that the power was on for 12 minutes and off for 10 minutes. Temperature of the molybdenum and of the fin were monitored with thermocouples. The fin reached a temperature between 585°C and 600°C during the on cycle, and cooled to

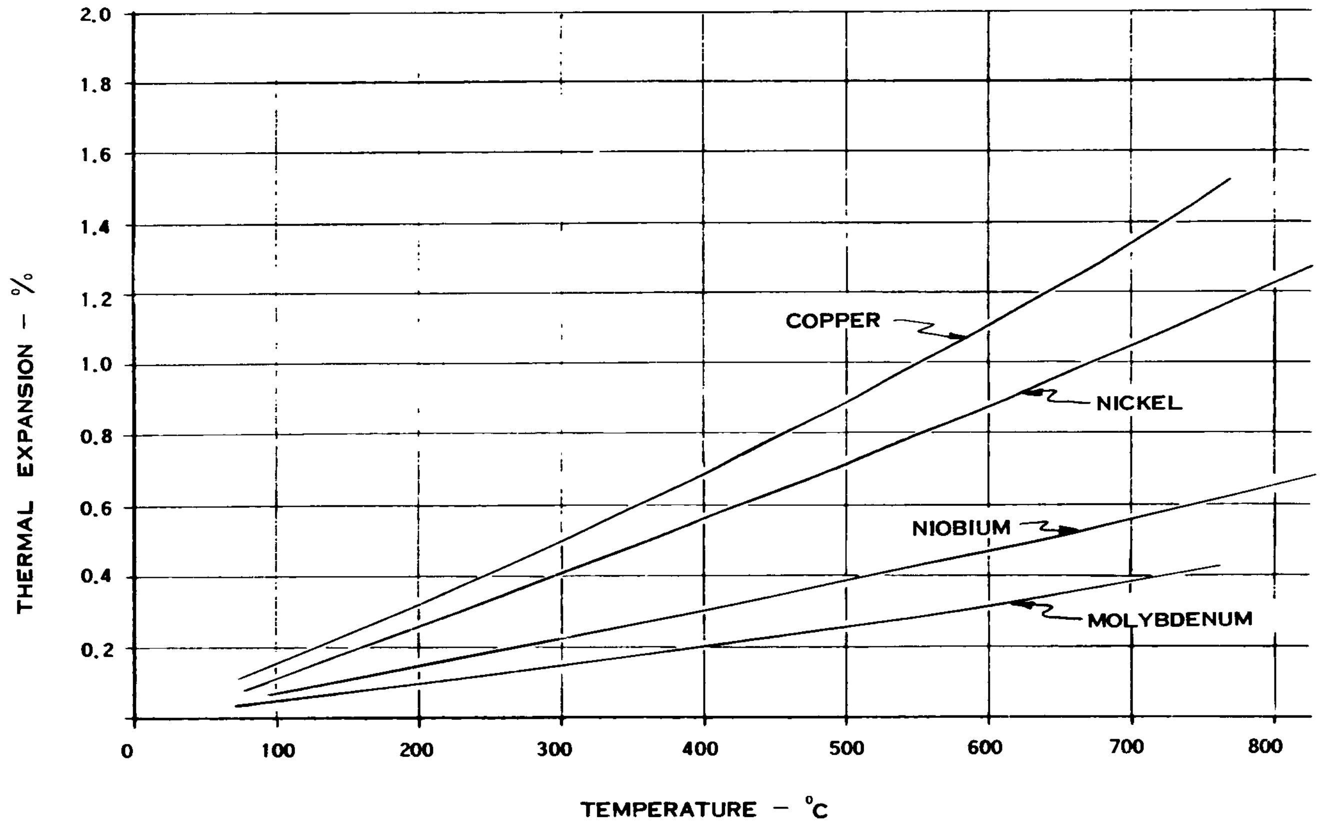


Figure 4. Thermal Expansion of Thermal Materials

$200^{\circ}C$ at the end of the off cycle. During the test, no change in the difference in temperature between the molybdenum pedestal and the fin root was noted. Such a change would have indicated a failure of one of the joints and hence a poor thermal contact in the assembly. The cycling was continued for approximately 800 cycles.

The piece was removed from the vacuum chamber, examined, and leak checked. A small leak had developed in the braze between the molybdenum anode pedestal and the niobium seal member. However, as previously noted, this was not a critical failure since this joint is not part of the vacuum envelope. All other joints were leak tight.

In order to correct the failure observed, a more ductile braze has been used in the fabrication of the C Series converters.

1.4 Spacing Pin Structure

To achieve a constant and known spacing between cathode and anode in both hot and cold conditions, a spacing pin structure has been used. This consists of tungsten pins seated in alumina cups that are, in turn, recessed into the anode. Figure 5 shows the pins in the anode with one pin removed to show the alumina cup. The alumina cups are located in the cooler anode, out of the plasma region, to prevent deterioration. Six pins are used around the periphery to maintain even spacing. The cathode seats directly on the end of the pins. The pins are ground to within .0001", and only the small thermal expansion of the pin and cup assembly itself changes the cathode-anode spacing between the cold and hot conditions. This thermal expansion is generally less than .0002".

Pressure of the cathode against the pins is maintained by a spring loaded tungsten tensile rod, welded to the cathode, which passes through the anode in the center hole shown in Figure 5. A flexible bellows in the envelope below the metal-ceramic seal, allows for thermal expansion mismatches.

Figure 5. Converter Anode with Spacing Pins

2.0 B SERIES CONVERTER TEST RESULTS

2.1 Converter B-1

Performance of this converter was reported in the Reference 2, but the testing of the converter has continued. The converter has operated over 90 hours. Power output varied during initial tests, reaching 6 watts/cm^2 at 1950^{o}K. During subsequent tests the power output declined to 4 watts/cm^2 and has remained constant during the latest 60 hours of operation. The converter was used in recent testing to check out the thermal cycling life test stations for the C Series converters and in its total operating life has been thermally cycled over 50 times.

2.2 Converter B-2

Testing of converter B-2 has been continued beyond the initial 50 hours reported in Reference 2. The result has been a significant increase in power output during the period from 50 to 70 hours. Power output has been steady over the latest 25 hours of test operation. A total of 95 hours has been accumulated on this converter and it is still in peak operating condition. B-2 has a molybdenum cathode and a nickel anode with .005" spacing. Performance of this converter, taken between 80 and 90 hours life,is shown in Figure 6 through 13. Because the performance showed promise of good low temperature operation, data was taken over the complete range from ignition at 1490^{o}K up to 2050^{o}K, although the converter design had been optimized for the 1750^{o}K to 1950^{o}K range. Maximum power output as a function of temperature is shown in Figure 6. Significant points along this curve at which data was taken are:

Temperature ^{o}K	Power Output Watts/cm^2
1500	1.7
1550	3.0
1650	4.9
1850	8.1
1950	9.6
2050	11.2

The E-I characteristics for all the temperatures at which data was taken are given in Figure 7. Characteristics showing variation of the E-I curves with cesium temperatures are plotted in Figures 8 through 13. All the data given in these figures was taken without anode heating.

2.3 Converter B-4

Converter B-4 has a rhenium cathode and a nickel anode with .0025" spacing. A total of 13 hours of operating time has been accumulated. Performance of this converter is given in Figures 14 through 20. Maximum power output as a function of temperature is shown in Figure 14. The E-I envelopes for the temperatures at which data was taken are given in Figure 15. The remaining figures show the individual E-I characteristics as a function of cesium reservoir temperature.

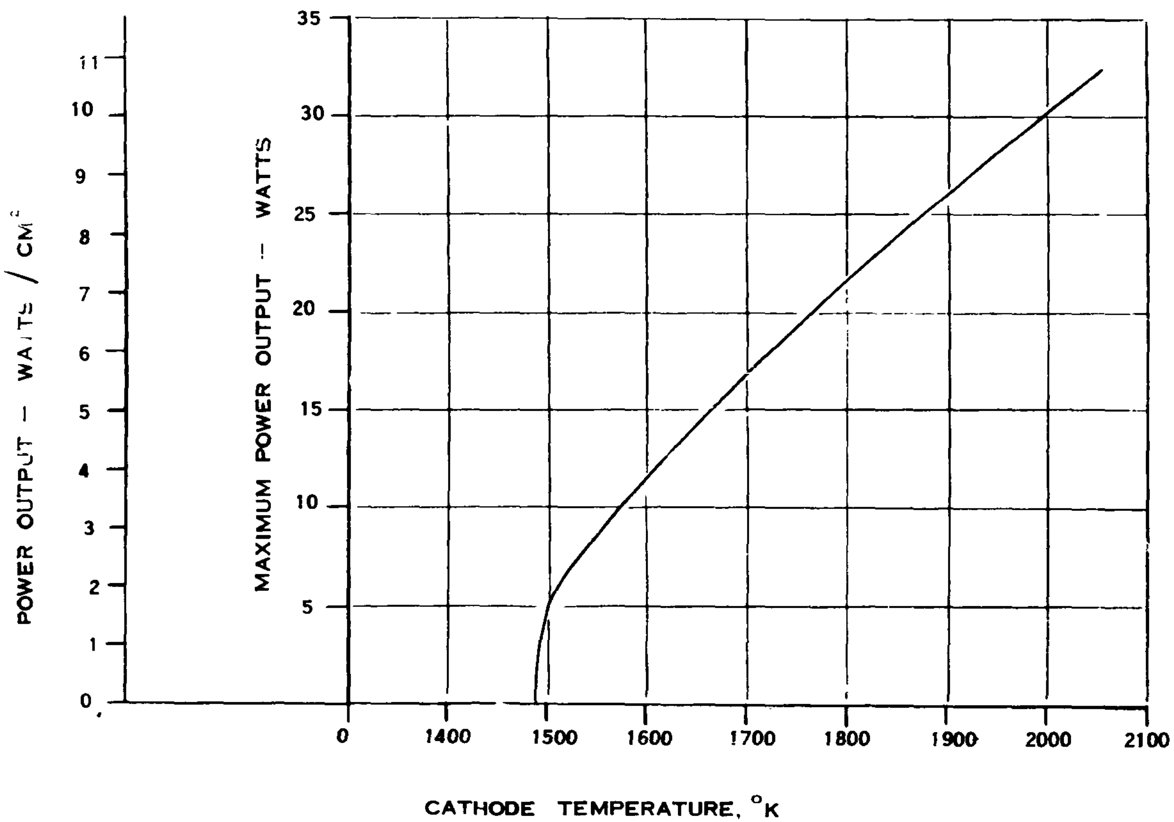


Figure 6. Maximum Power Output - Converter B-2

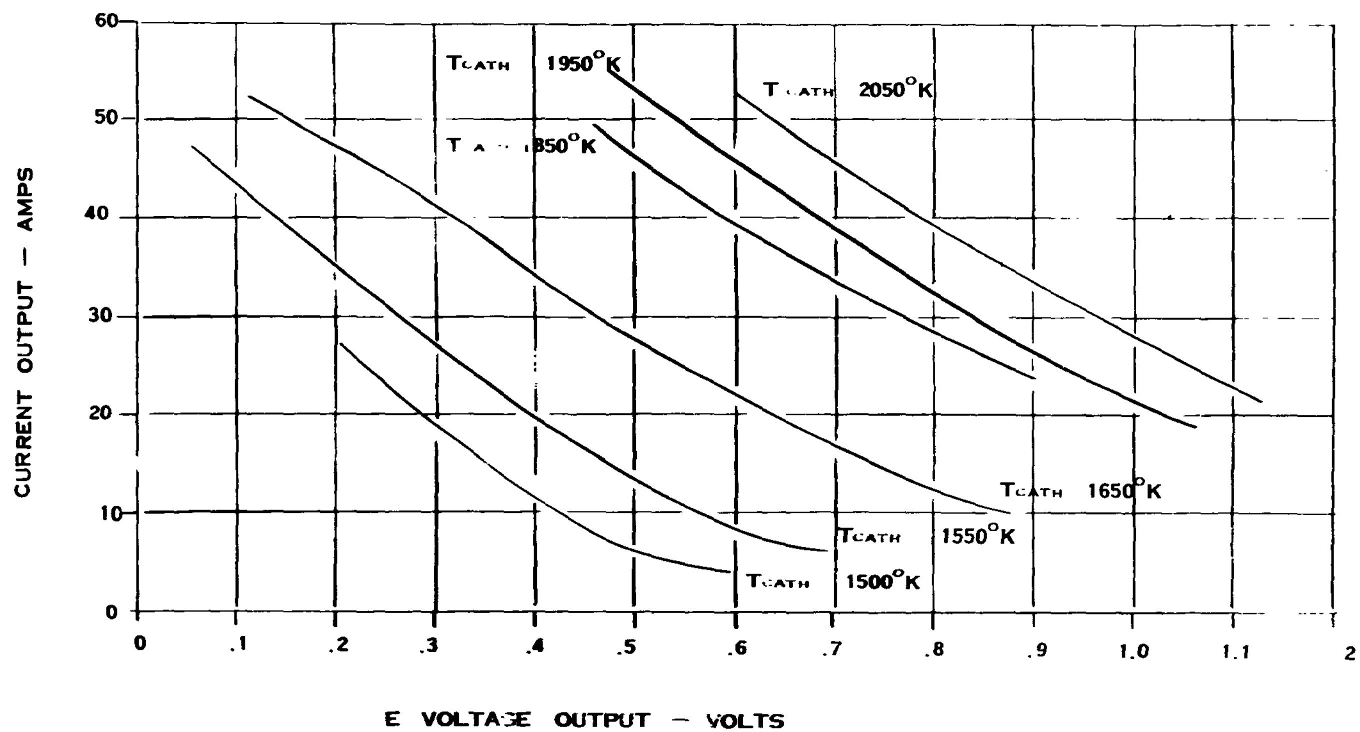
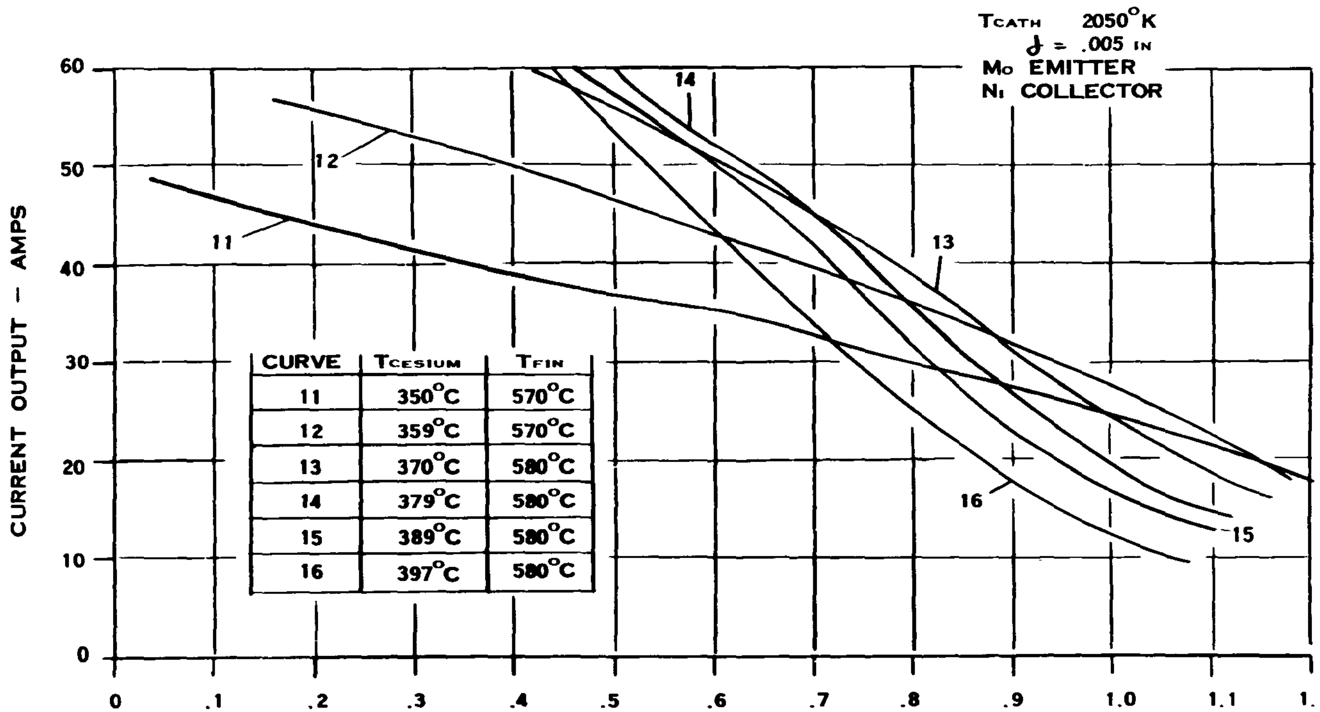


Figure 7. E-I Characteristics - Converter B-2



CURVE	T_{CESIUM}	T_{FIN}
11	350°C	570°C
12	359°C	570°C
13	370°C	580°C
14	379°C	580°C
15	389°C	580°C
16	397°C	580°C

Figure 8. E-I Characteristics at 2050°K - Converter B-2

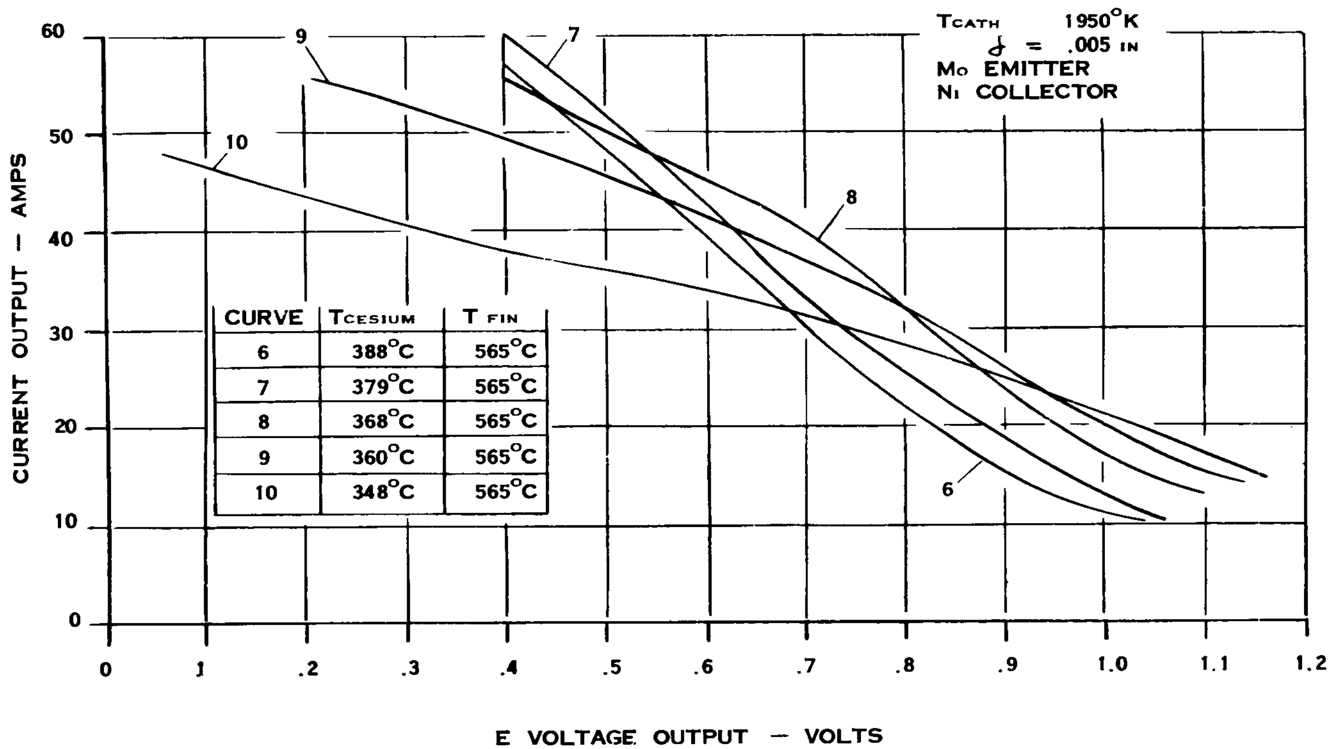


Figure 9. E-I Characteristics at 1950°K - Converter B-2

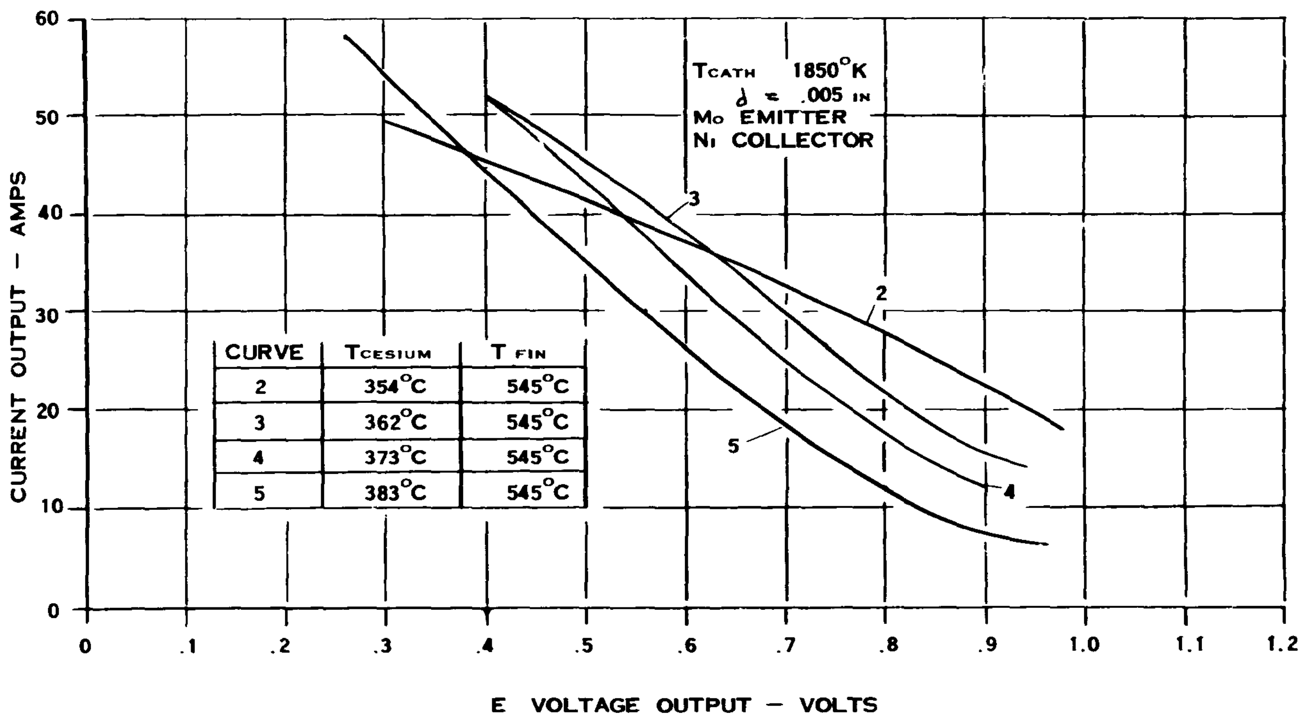


Figure 10. E-I Characteristics at 1850°K - Converter B-2

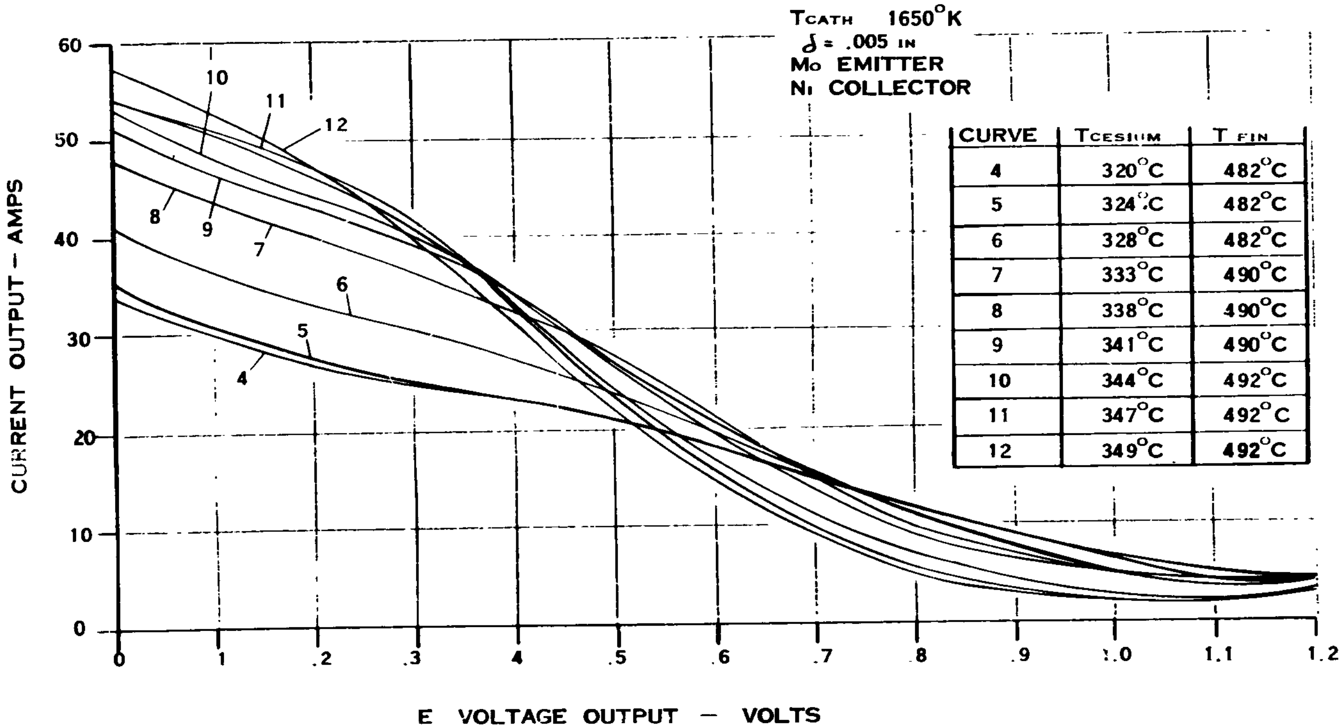
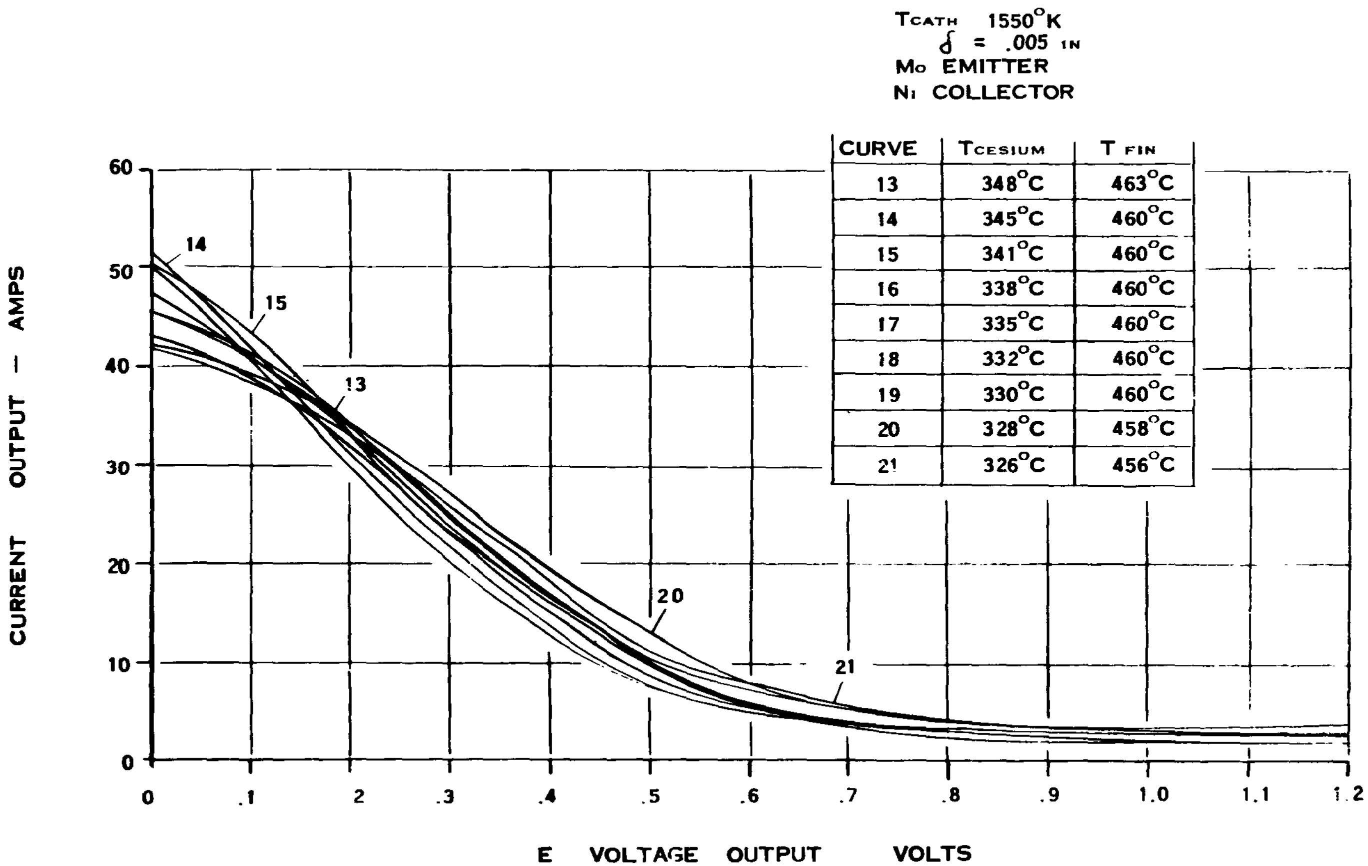


Figure 11. E-I Characteristics at 1650°K - Converter B-2



CURVE	TCESIUM	T FIN
13	348°C	463°C
14	345°C	460°C
15	341°C	460°C
16	338°C	460°C
17	335°C	460°C
18	332°C	460°C
19	330°C	460°C
20	328°C	458°C
21	326°C	456°C

Figure 12. E-I Characteristics at 1550°K - Converter B-2

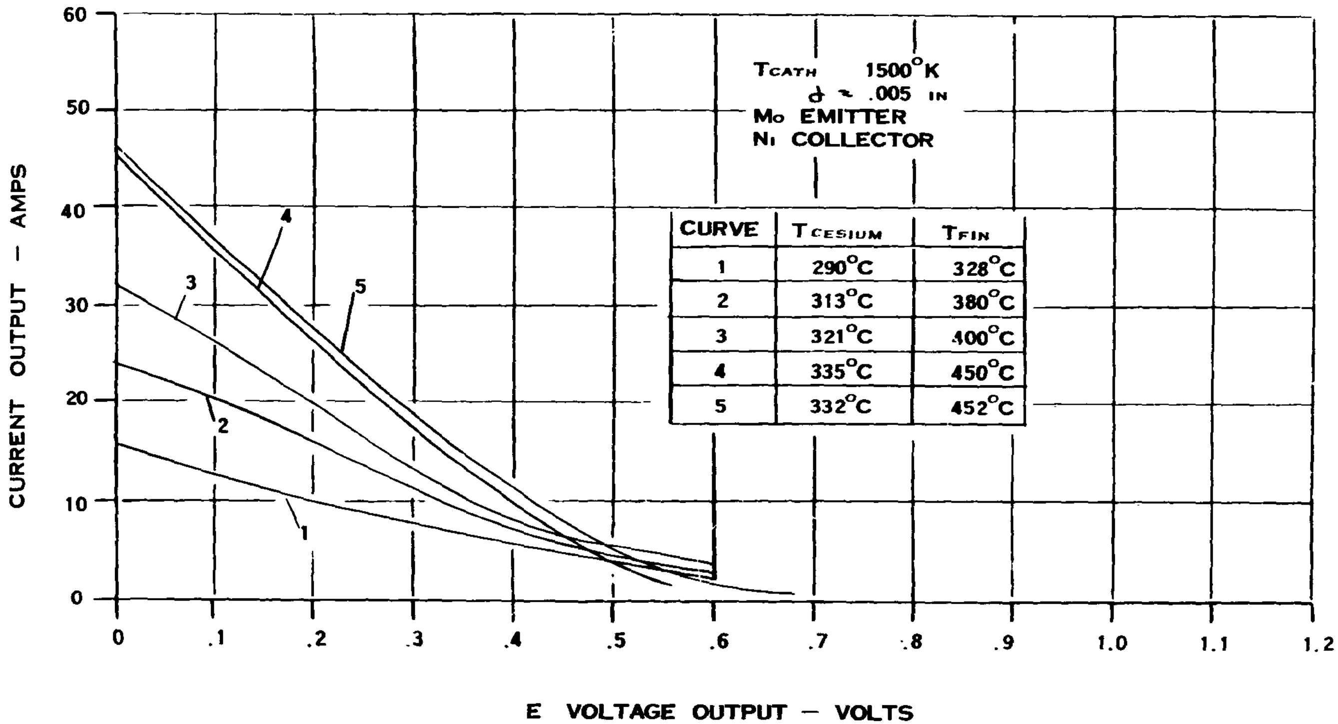


Figure 13. E-I Characteristics at 1500°K - Converter B-2

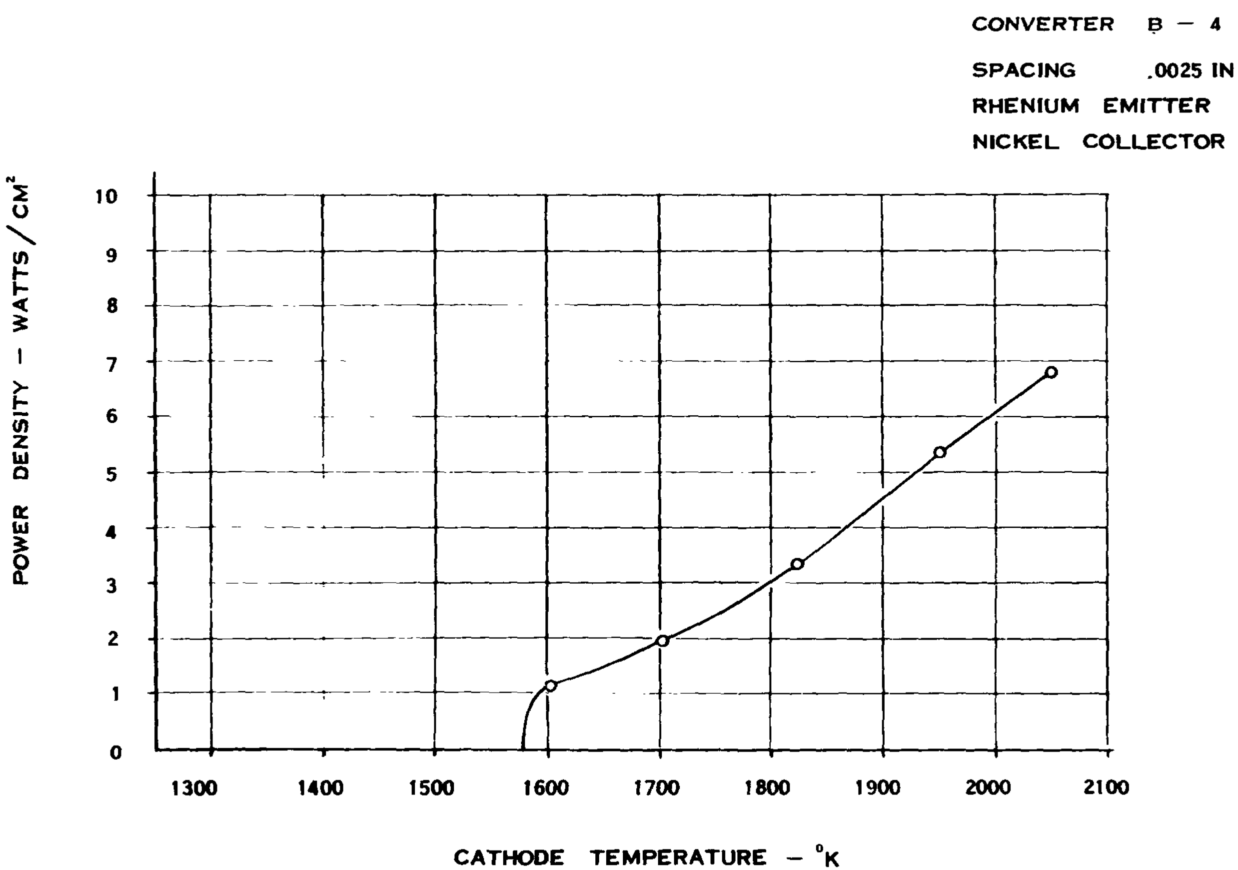


Figure 14. Maximum Power Output - Converter B-4

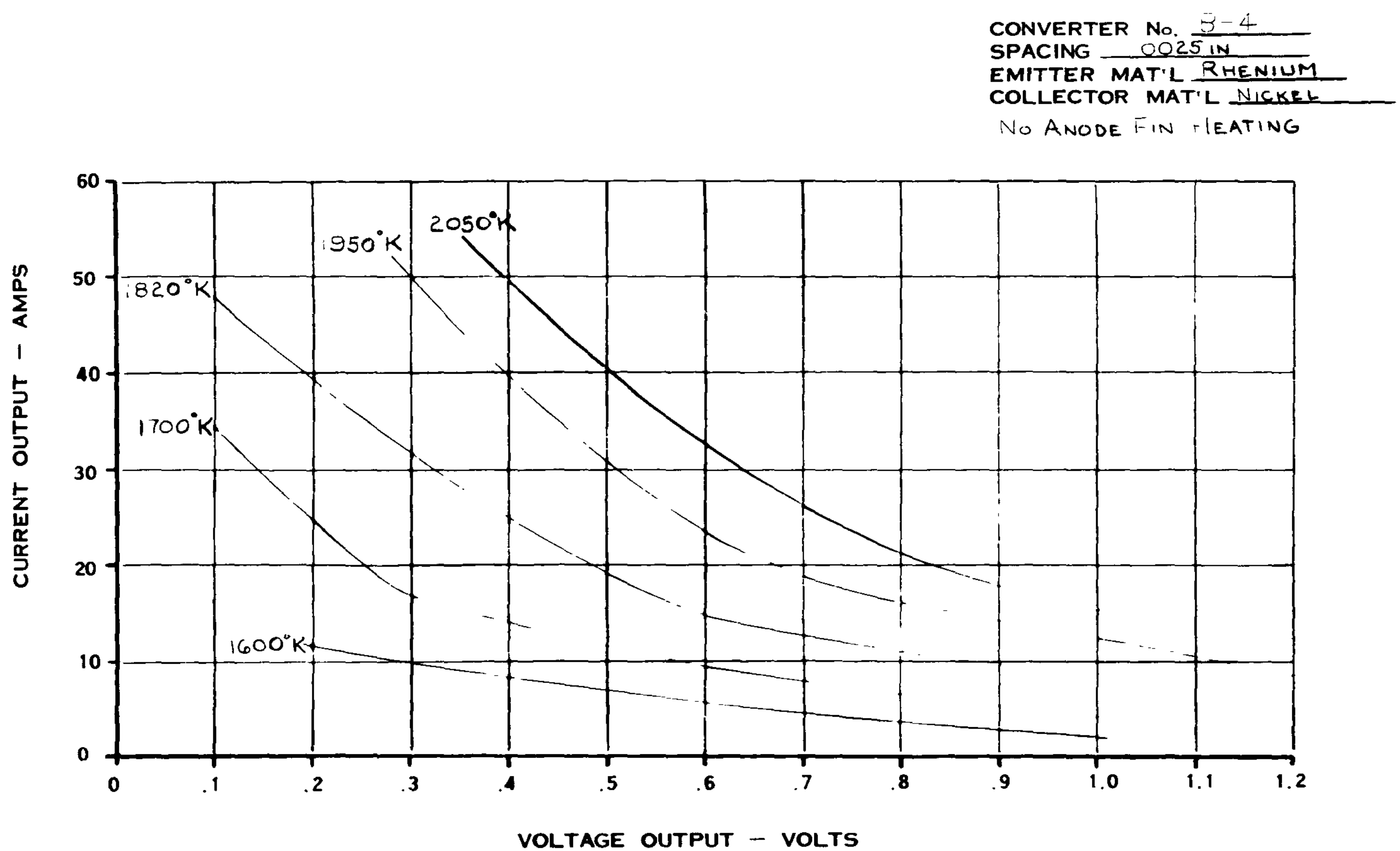


Figure 15. E-I Characteristics - Converter B-4

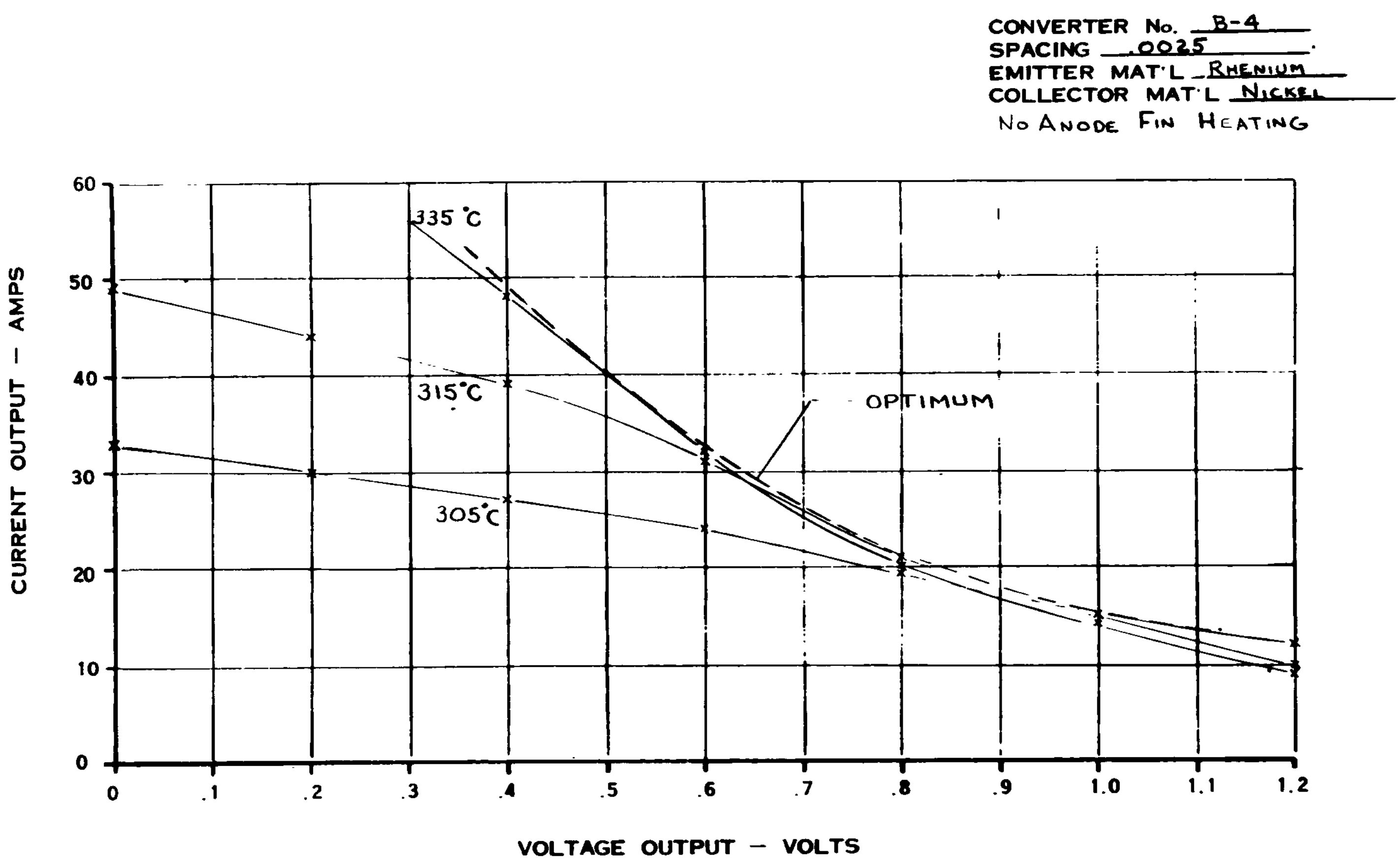


Figure 16. E-I Characteristics at 2050°K - Converter B-4

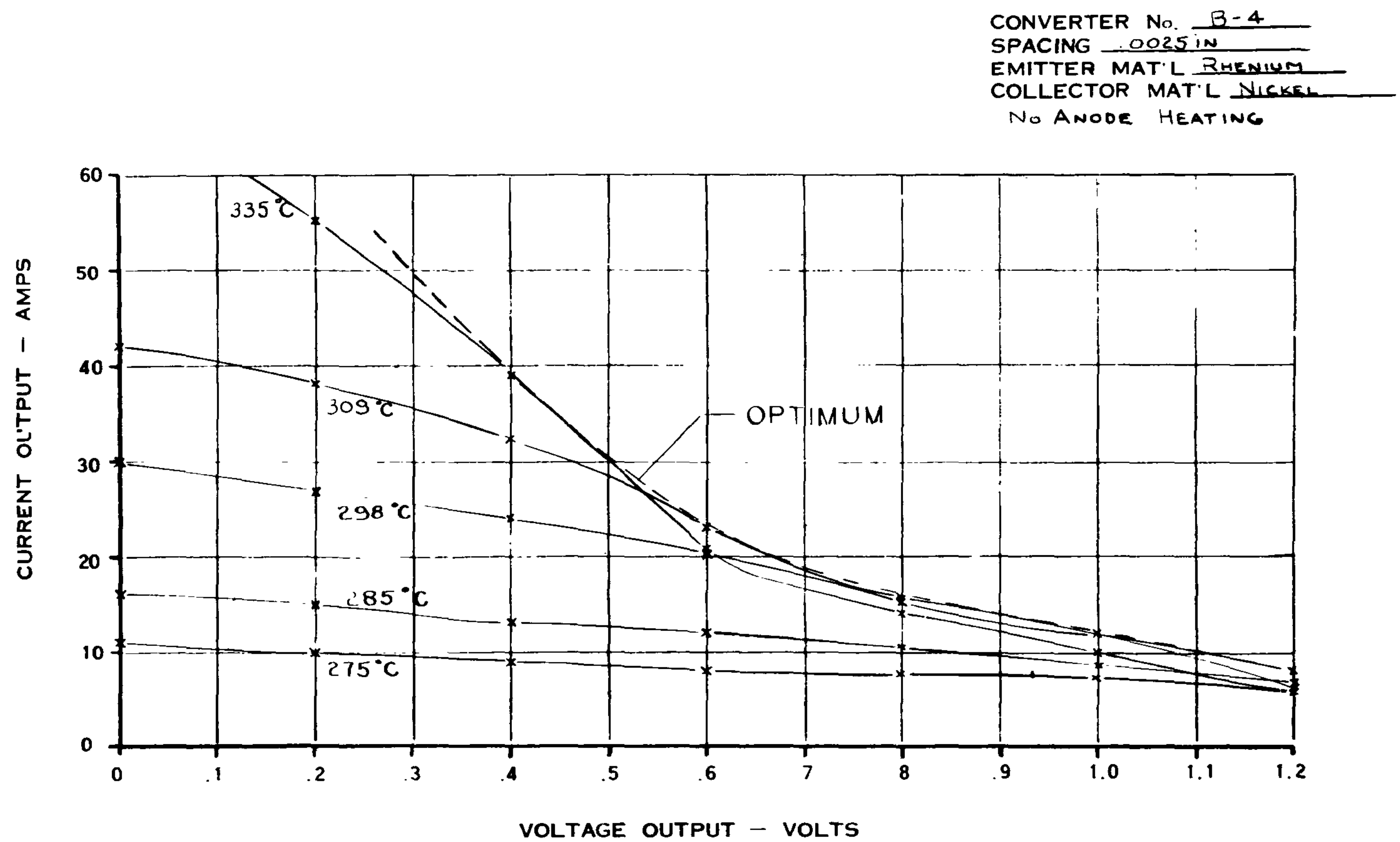


Figure 17. E-I Characteristics at 1950^{o}K - Converter B-4

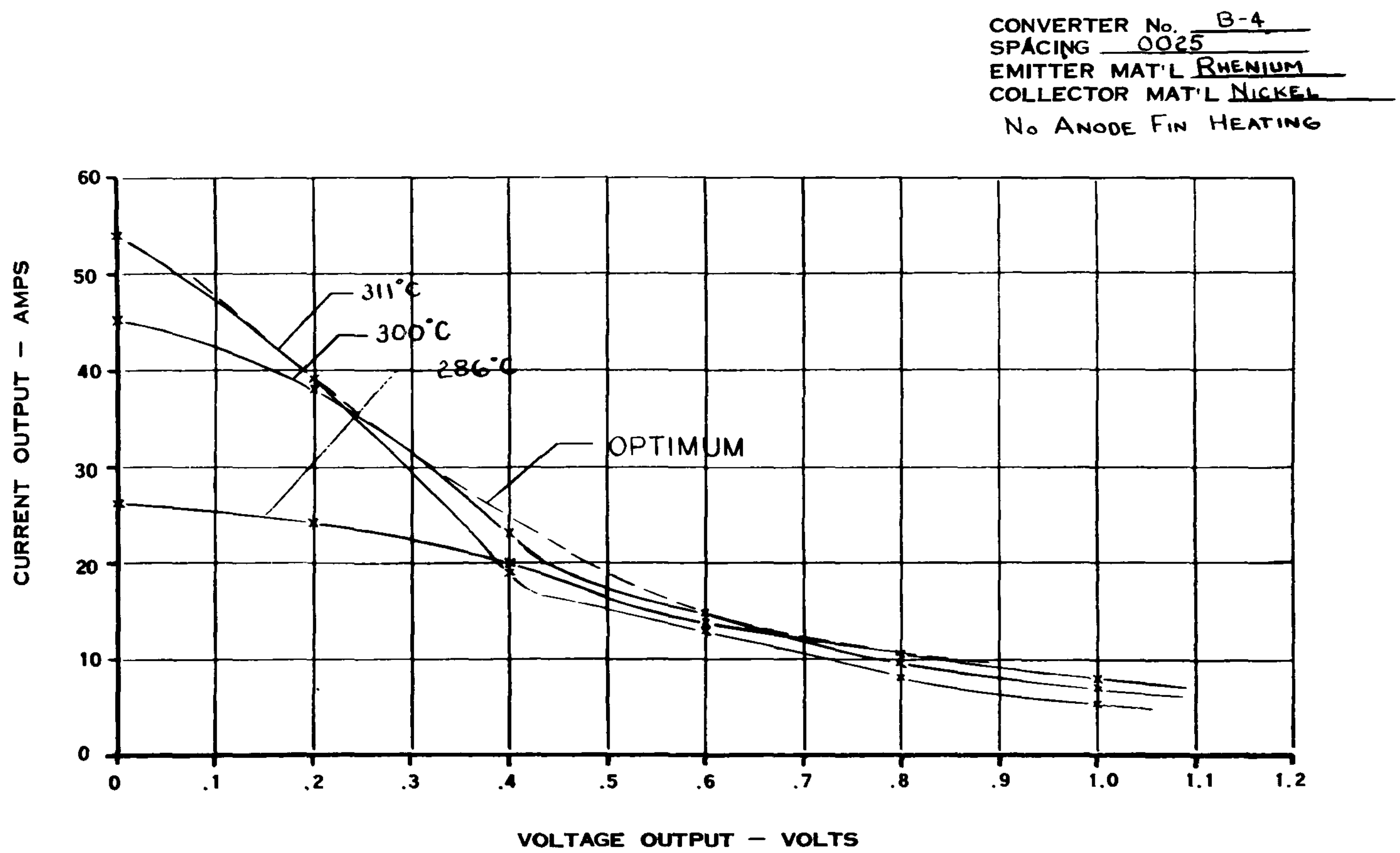


Figure 18. E-I Characteristics at 1820°K - Converter B-4

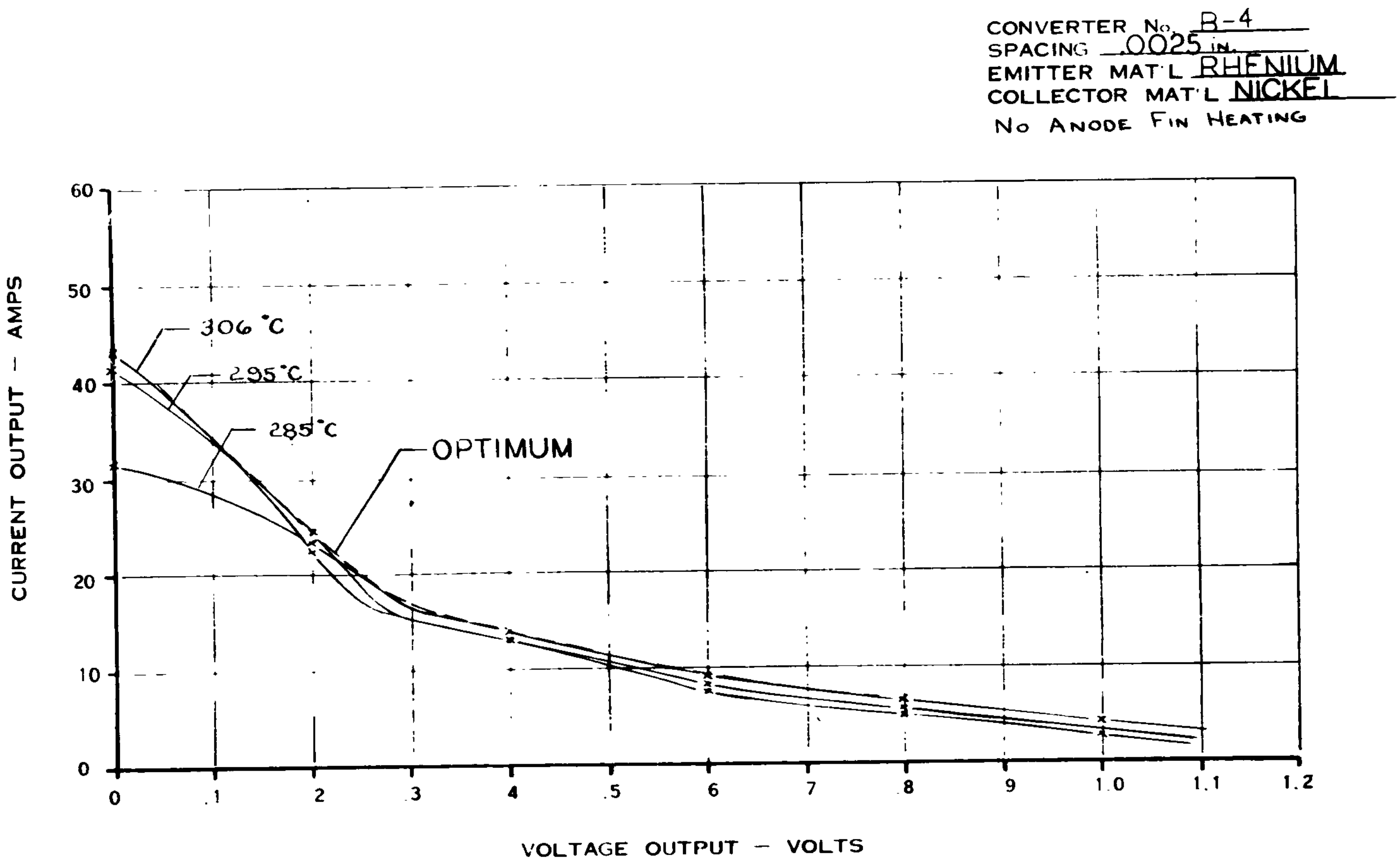


Figure 19. E-I Characteristics at 1700°K - Converter B-4

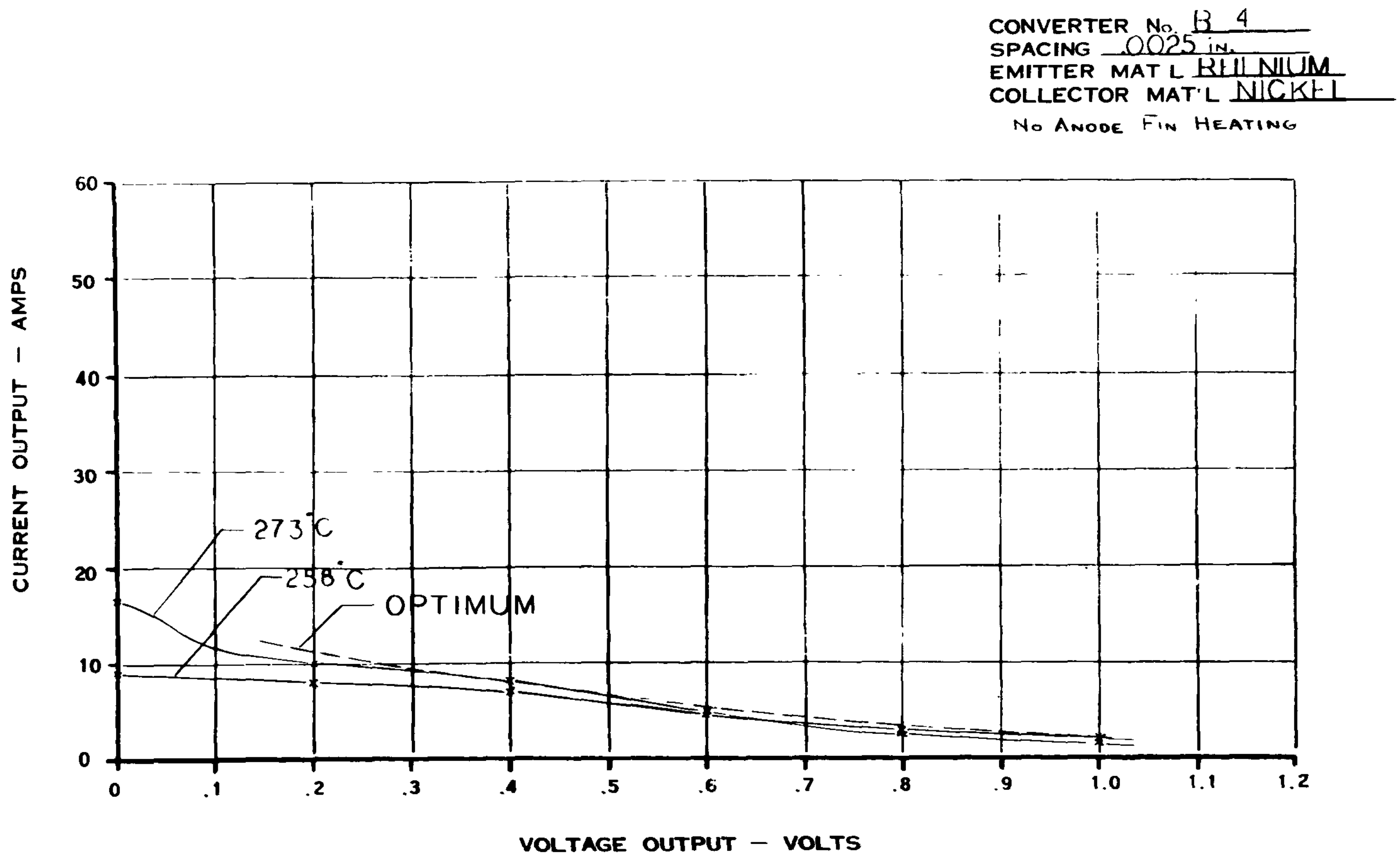


Figure 20. E-I Characteristics at 1600°K - Converter B-4

3.0 C SERIES CONVERTER TEST RESULTS

3.1 Life Test Specification

The STEPS III C Series converters are to be performance and life tested to prove structural integrity at high performance in the design temperature range of 1750-1950°K. The following test is set up to be a standard by which to judge these qualities. Test objectives are to identify modes of structural failure or performance degradation so they can be corrected in succeeding designs. The test is essentially one to qualify early engineering development model converters for consideration in thermionic systems development. This testing is particularly important for new converter designs, such as the STEPS III converters, to prove feasibility of welds, brazes, material characteristics, and mechanical structure.

At the present stage of thermionic converter development, specifications for life tests may seem quite arbitrary. There exists a need, however, for a standard qualification test, to qualify converter designs for inclusion in the development of solar thermionic systems in the applications and temperature ranges most likely within the next few years.

Based on life tests that have been conducted and on projected requirements for thermionic system development and application, certain criteria can be established. First of all, converters have often produced high initial output, only to degrade to some steady state power within the first 20 to 100 hours. Occasionally, increases in power have also been noted in this early period of operation. Power output reported in Reference 3 has been relatively steady beyond this period, however, until some structural failure such as an envelope leak caused severe degradation. A two-hundred-hour test at steady state should include most of these initial variations and reveal any gross structural weaknesses.

Cycling should be part of the test to simulate the more severe conditions of an orbital application without thermal storage. The period of cycling was chosen to simulate a near earth orbit. Cycling should be an especially important test for structural integrity of the welds and brazes between dissimilar materials in the converter. However, at this stage of development, some steady state operation is desirable to note gradual changes in performance versus time, so a combination of cycling and steady operation should make up this life test.

A total test time of approximately 500 hours would be comparable to that which should be required for early flight experiments. It can be run in a relatively short period compared to the design and fabrication cycles and so should be useful for early engineering-model converter design qualification. In later stages of converter development, longer life tests will be required, but the present state-of-art does not require 10,000 hour testing. It is anticipated that, as converters are fabricated to reliably pass this 500 test, some will be kept on test until failure, and the life thus extended.

While the design temperature range for the STEPS III program is 1750-1950°K, it is felt that test operation at the highest temperature, 1950°K, is required to present more severe criteria for failure.

Therefore, the test for the C Series converters was specified to be:

510 hours, consisting of (in order)

200 hours steady state
140 cycles, 60 minutes on, 30 minutes off
100 hours steady state

The operating point was specified as:

Cathode Temperature: 1950^{O}K
Cesium Reservoir Temperature: Optimum power
Anode Fin Temperature: Optimum power

Cycling will be accomplished by cycling the high voltage of the electron bombardment heater. Since the cesium reservoir is not designed to be thermally coupled to the cathode for fast warmup in the C Series converters, it will be electrically heated and maintained at optimum throughout the test. The anode fin, if electrical heating is required to maintain optimum, will be thermally cycled along with the main heat supply.

Tests with converters B-1, and later C-3, showed that the cathode temperature dropped approximately 800^{O}C in the first minute following high voltage cut off. The cathode temperature eventually reached about 400^{O}C in the 30 minute off-period. This low point closely duplicates the temperature reached by the Cavity Vapor Generator in similar solar cycling tests at the Phoenix Solar Test Facility (Reference 1). At the beginning of a cycle, the temperature rose 1200^{O}C in the first minute, and the converter began producing power within 4 minutes of the start of the cycle.

3.2 Converter C-3 Life Test

Converter C-3 completed 522 hours of operation at 1950^{O}K, including 210 hours of thermal cycling, without failure of any part and the converter is still operable. The power output degraded about 30% from the initial 8.5 watts during the total test. This test, previously outlined in section 3.1, was conducted to prove structural integrity and to investigate performance characteristics. This C-3 converter has a tantalum anode and cathode, with .005" spacing. Planar area of the cathode is a nominal 3 cm^{2}. The converter is shown in Figures 1 and 2. It was mounted with the centerline horizontal, as shown in Figure 21. Figure 21 also shows how the cathode was surrounded by multiple-layer radiation shielding to protect the region around the seal and the cathode current leads, just as would be done in a generator.

Performance of the converter during its 522 hour test is summarized in Figures 22 and 23. Figure 22 shows the power output versus time. Figure 23 shows the E-I characteristics taken initially and at each 100 hours throughout the test. Optimization of the anode temperature and the cesium temperature was also done. Figure 24 shows power output as a function of both anode and cesium reservoir temperature at the 1950^{O}K cathode temperature. The individual E-I characteristics showing variation with cesium reservoir temperature, as taken each 100 hours throughout the test, are given in Figures 25 through 30. This data is presented without detailed analysis to permit its timely inclusion in this report. A complete analysis will appear in the next quarterly report.

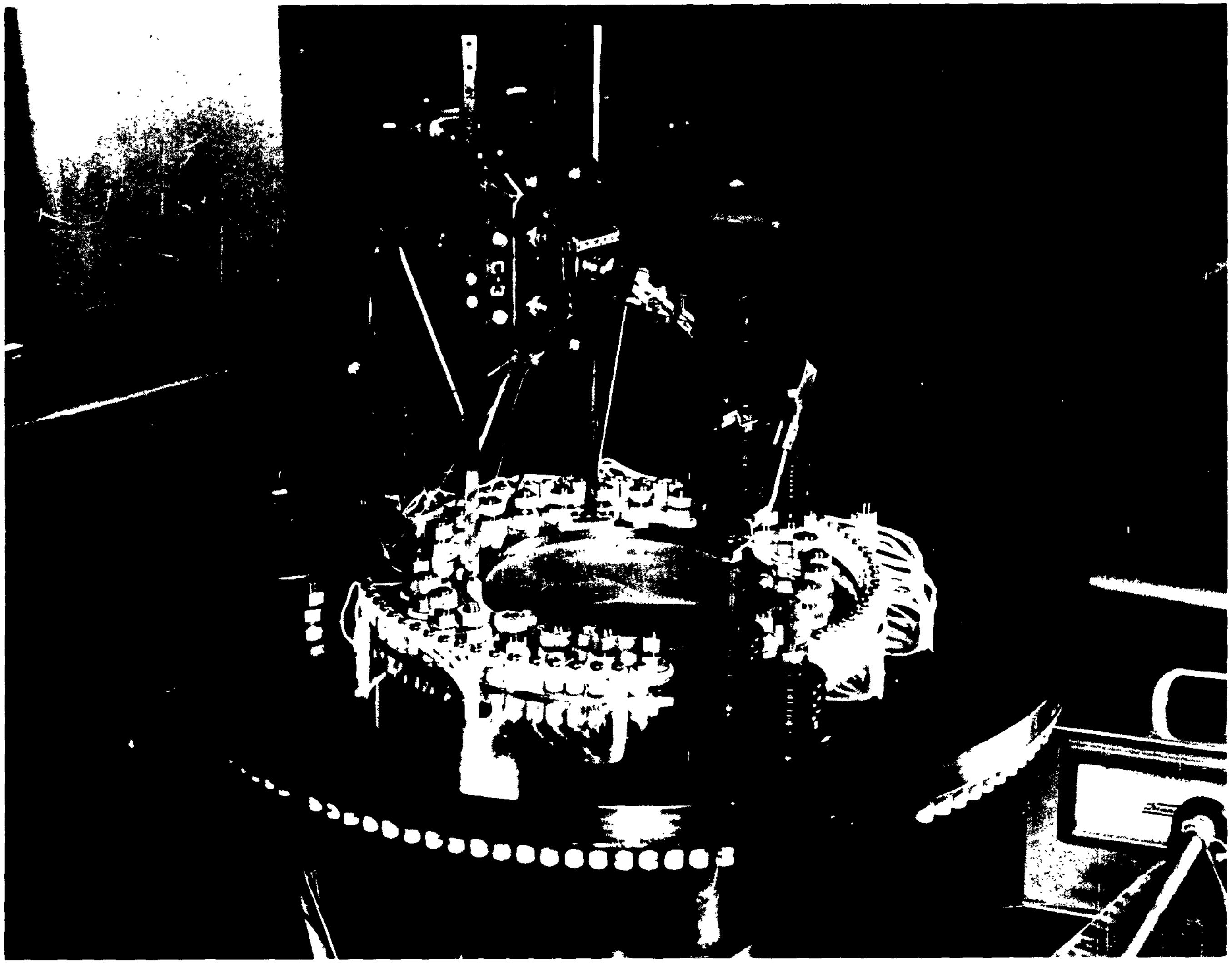


Figure 21. Converter C-3 on Life Test

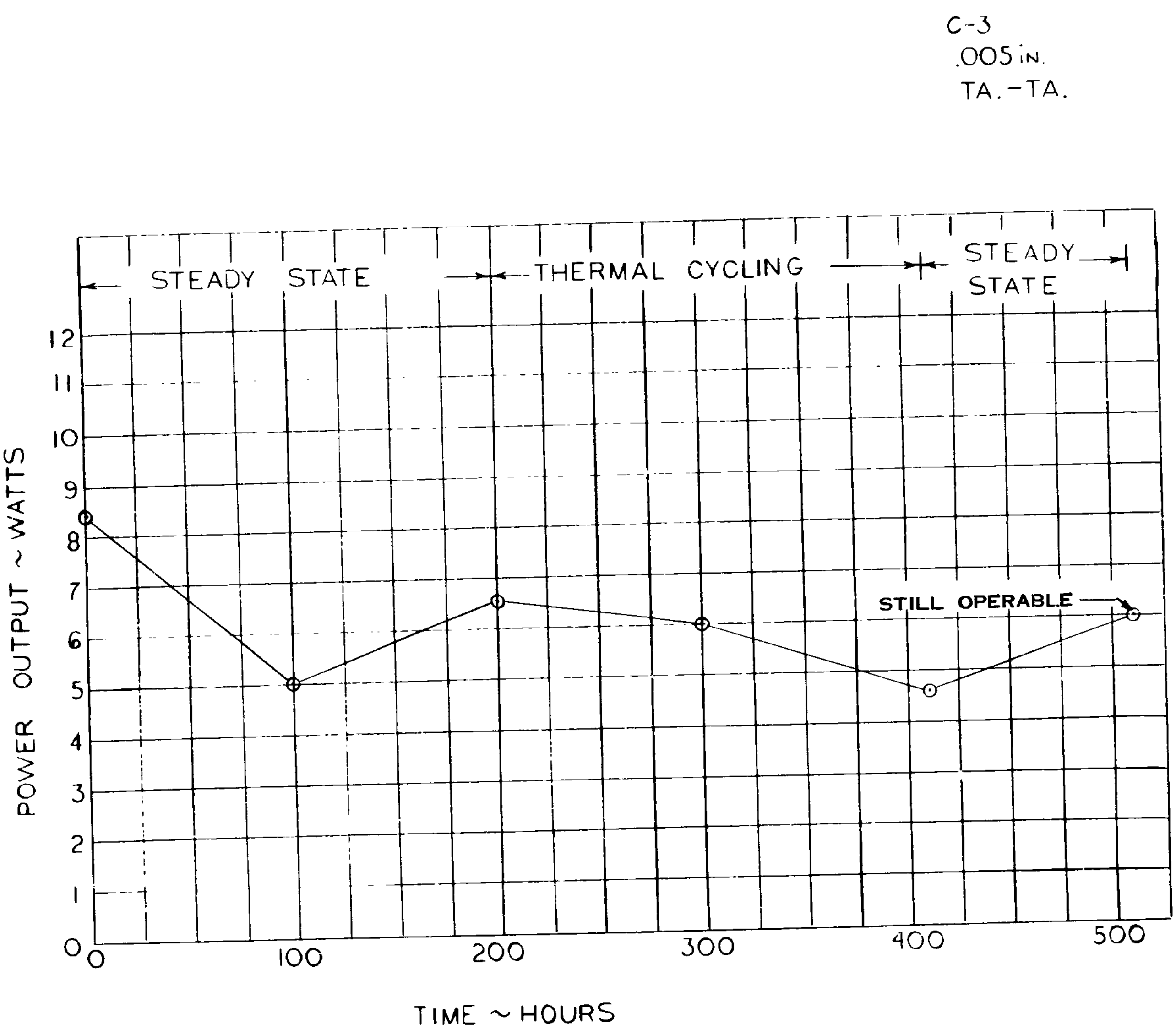


Figure 22. Converter C-3 Peak Power at 1950°K Throughout Life Test

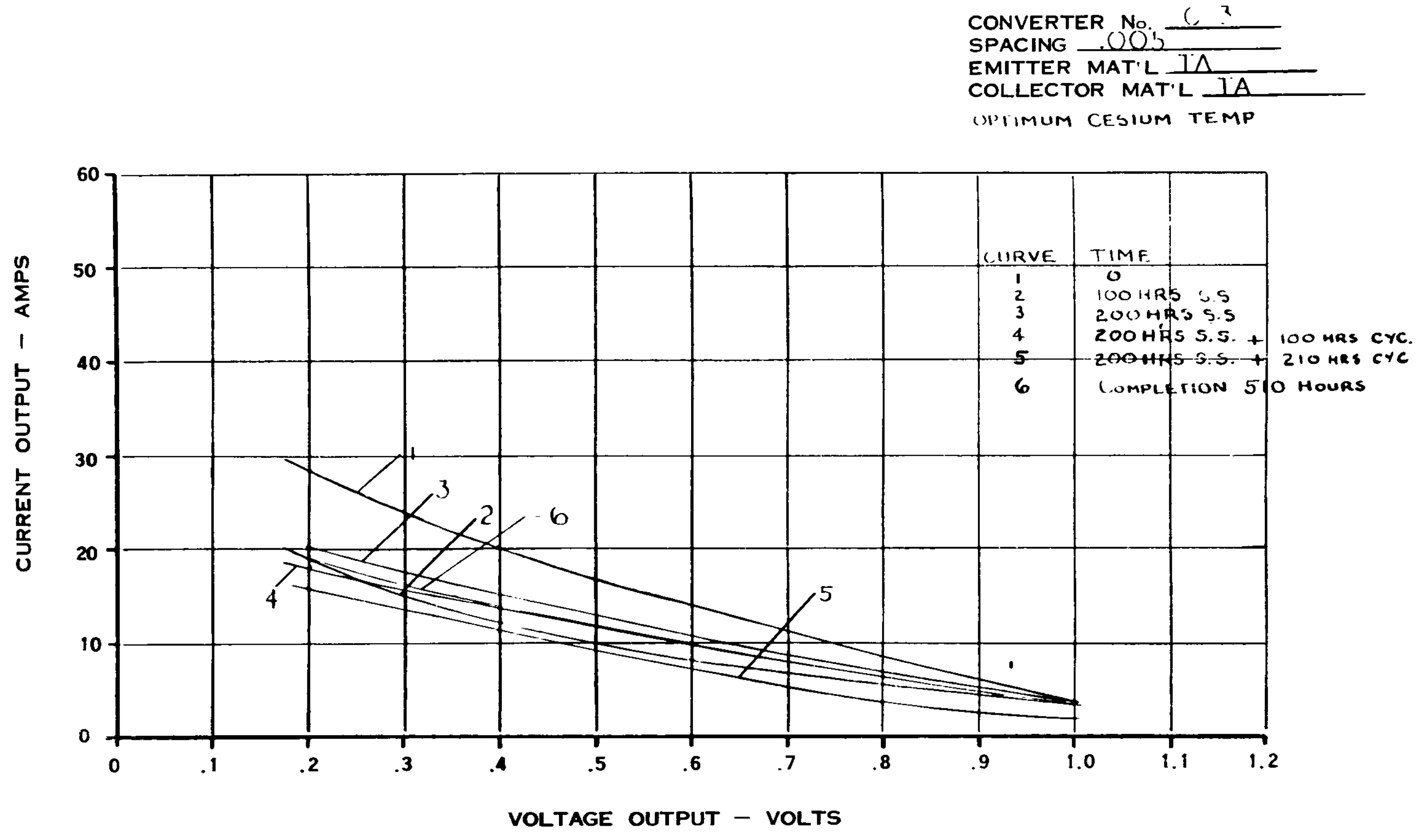


Figure 23. C-3 E-I Characteristics Throughout Life Test

CONVERTER C – 3

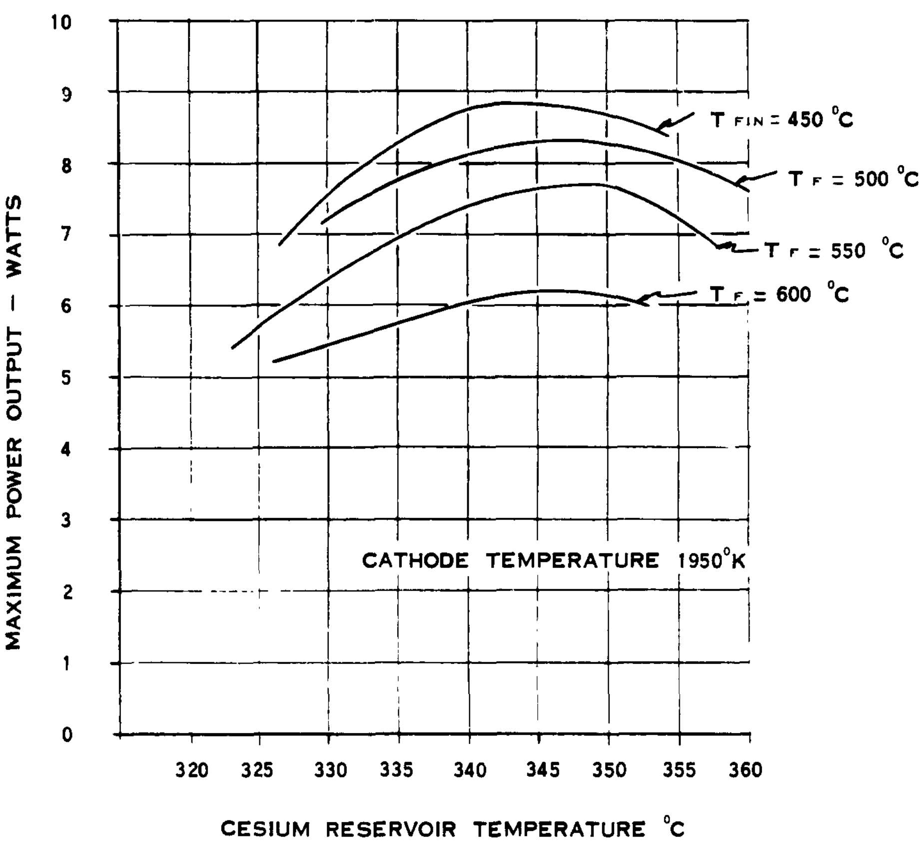


Figure 24. Power Output Variation with Anode and Cesium Temperatures

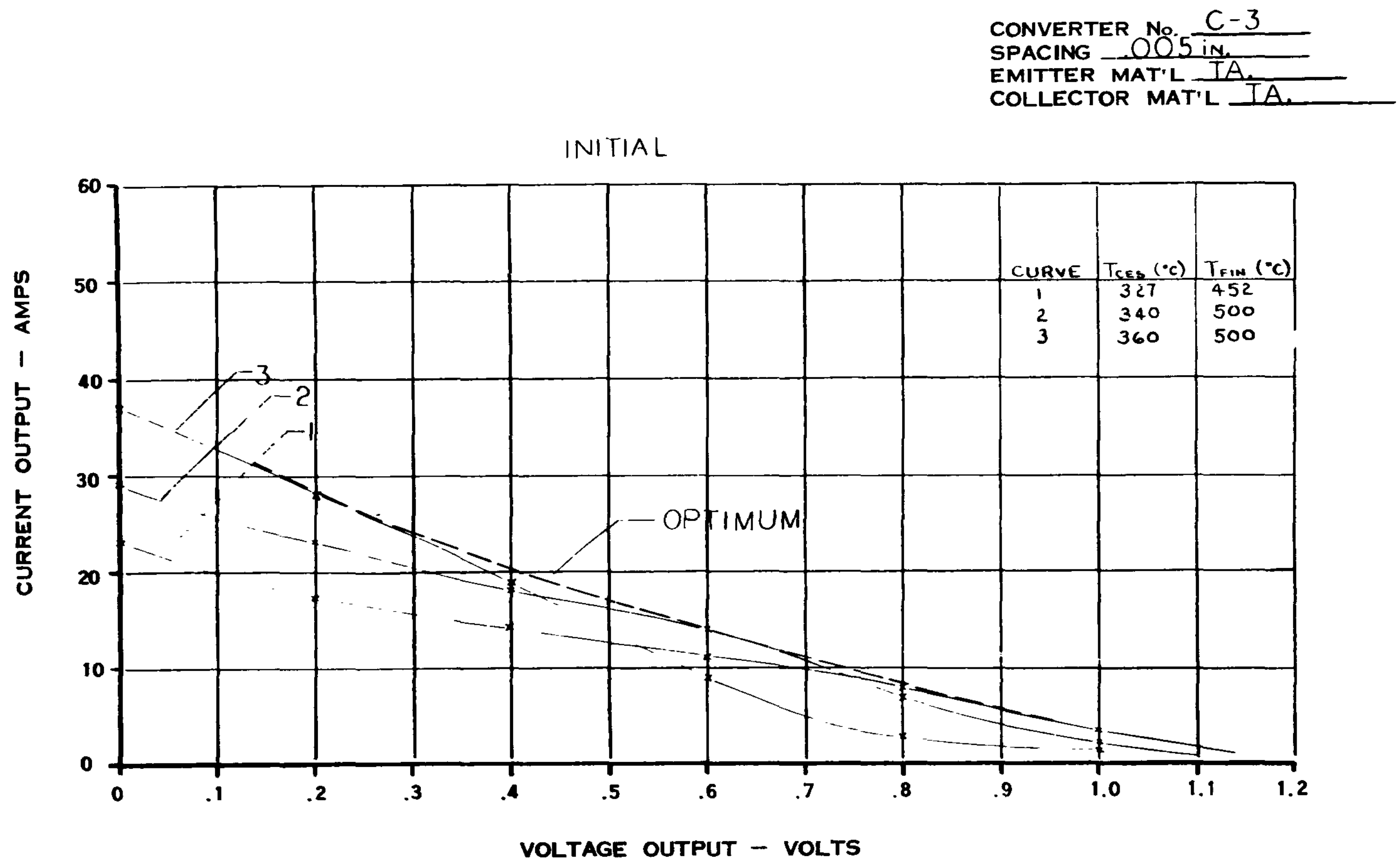


Figure 25. E-I Characteristics at 1950°K - Initial

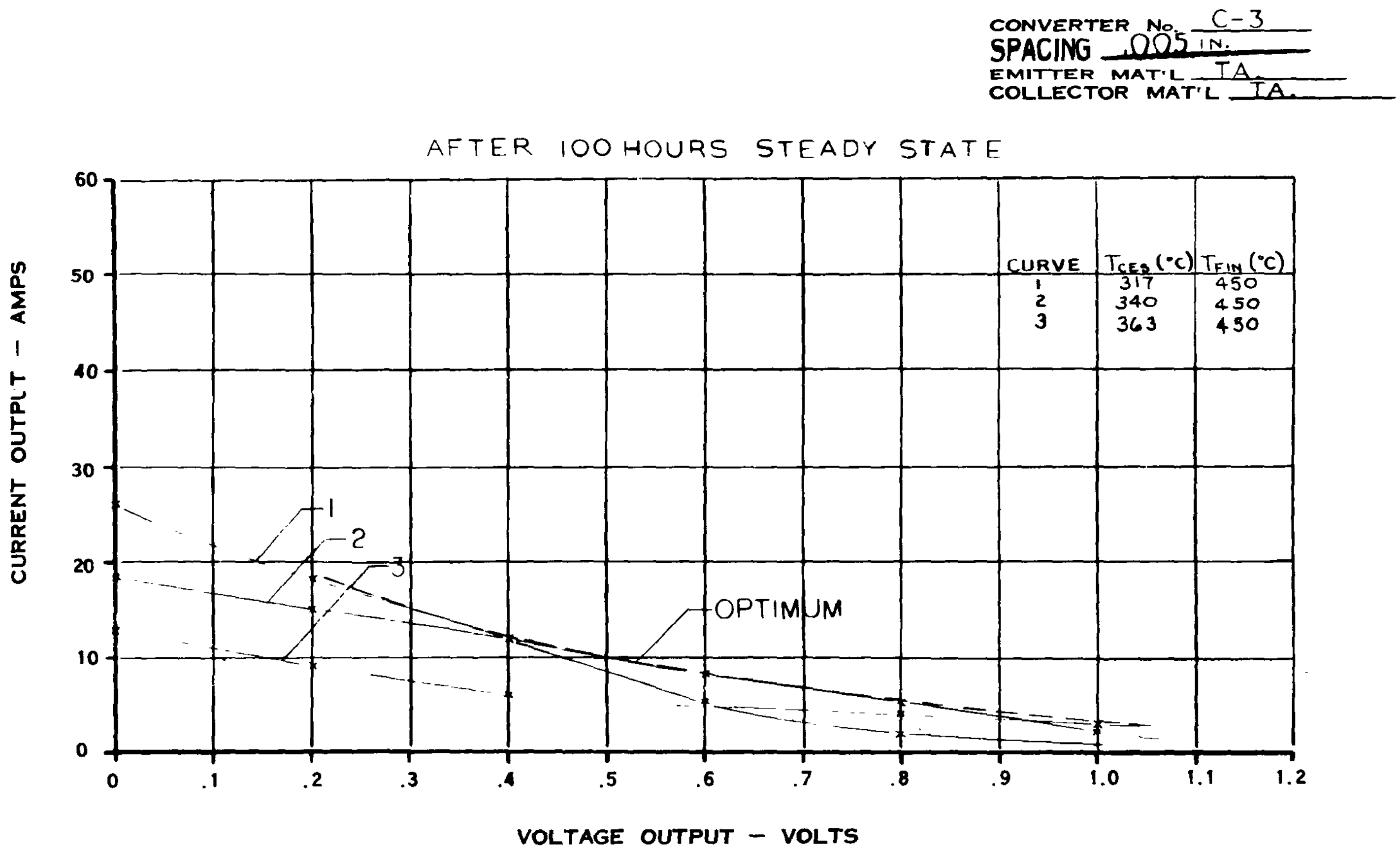


Figure 26. E-I Characteristics at 1950°K - 100 Hours

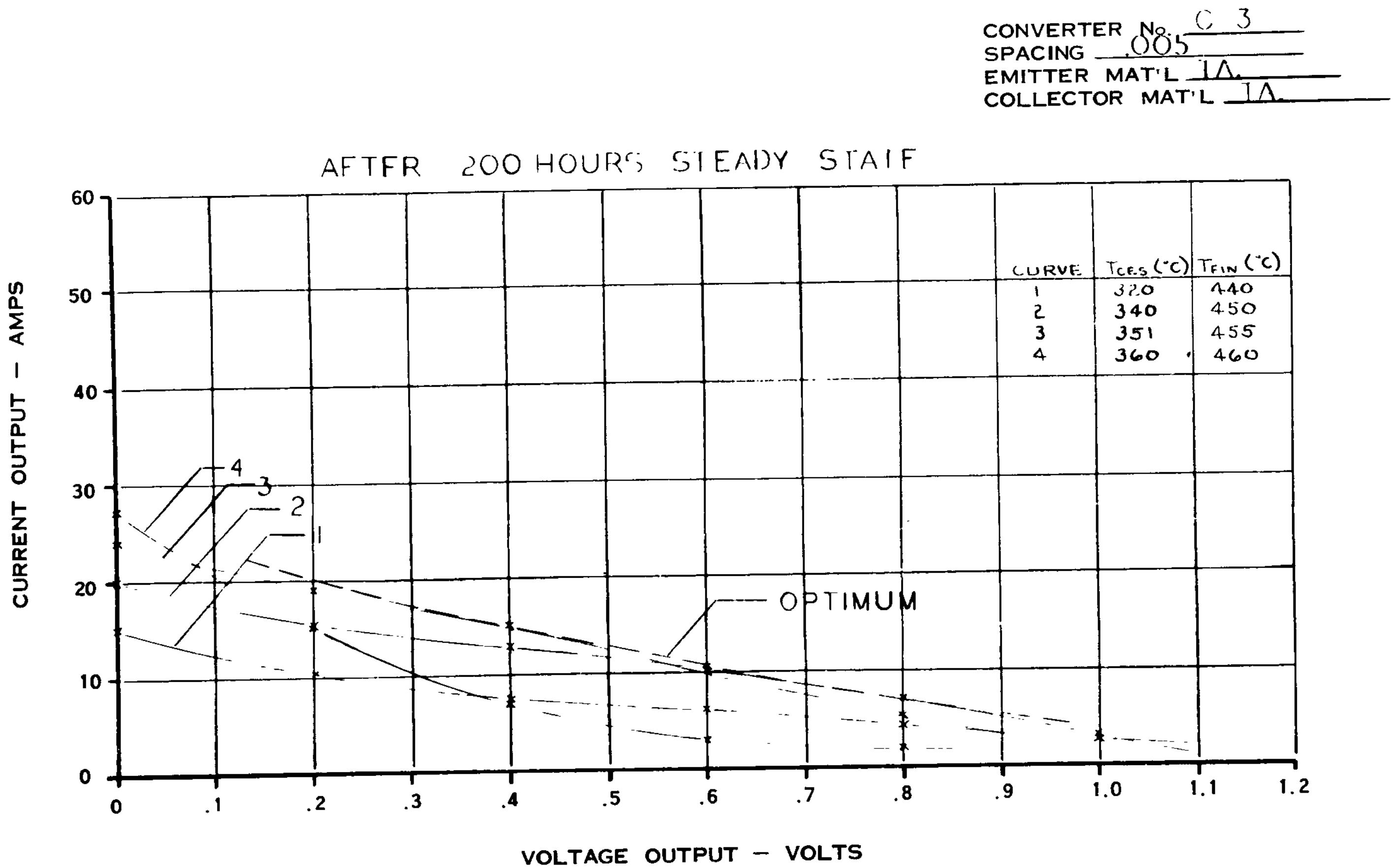


Figure 27. E-I Characteristics at 1950°K - 200 Hours

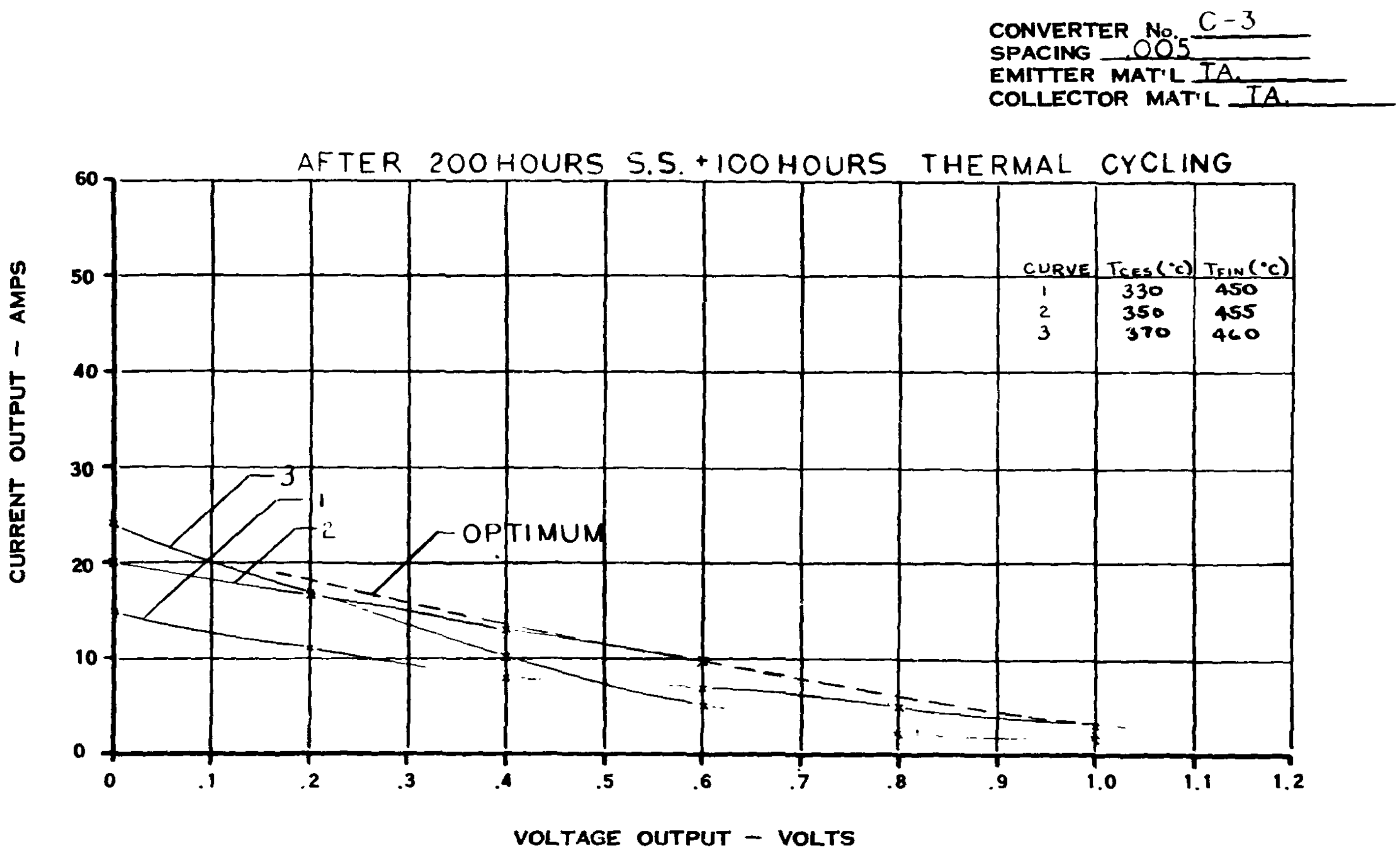


Figure 28. E-I Characteristics at 1950°K - 300 Hours

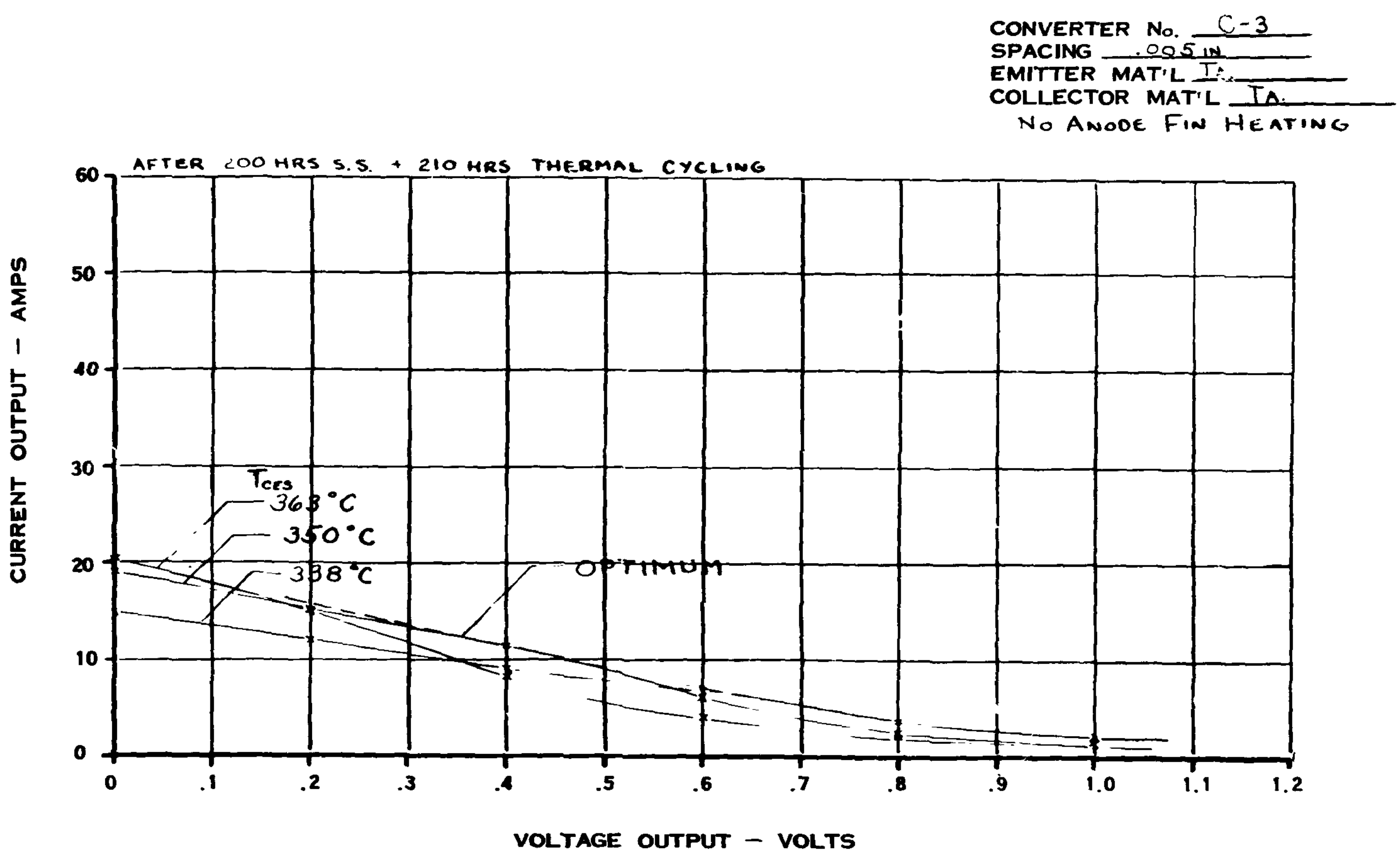


Figure 29. E-I Characteristics at 1950°K - 410 Hours

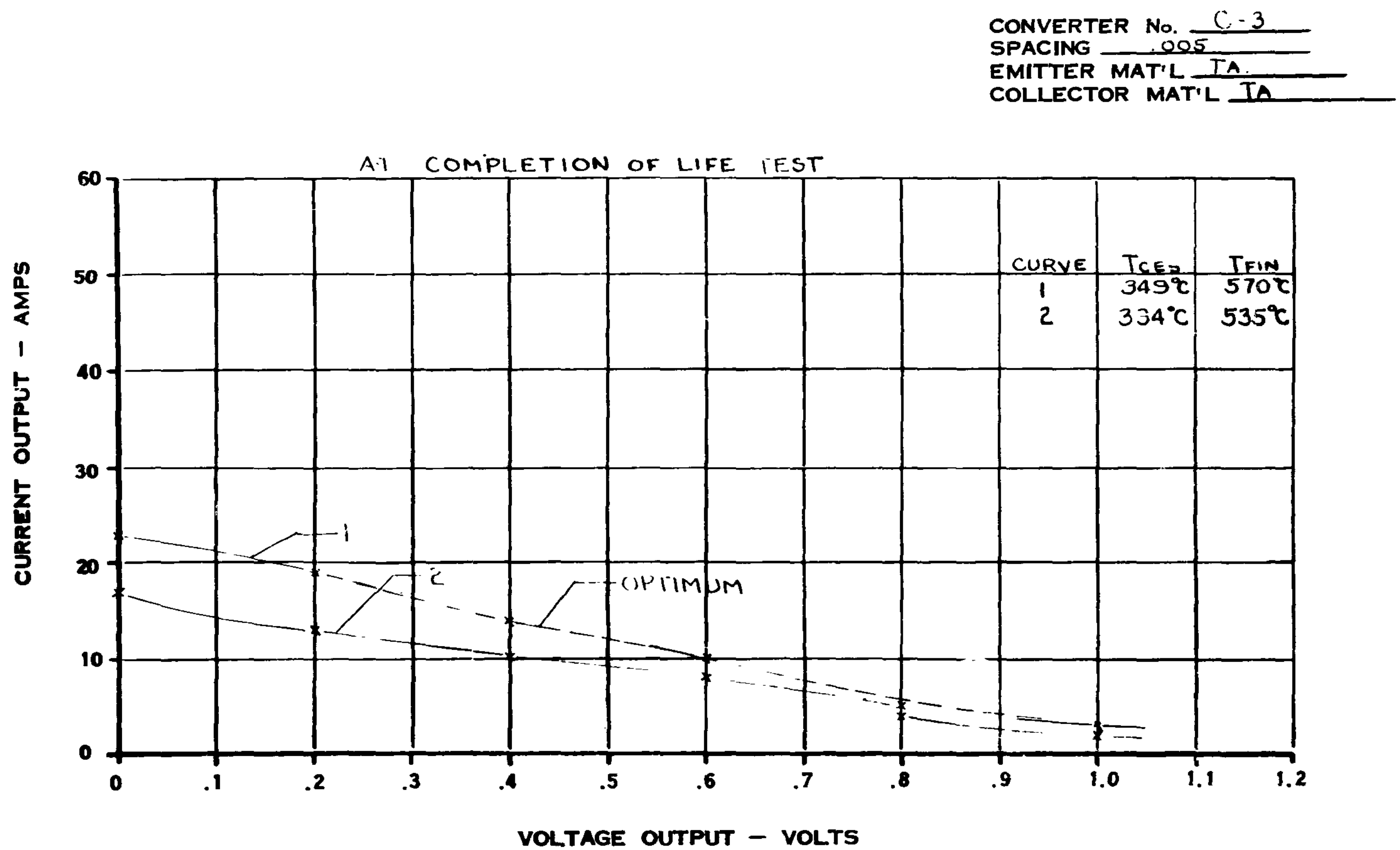


Figure 30. E-I Characteristics at 1950°K - 520 Hours

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